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APOLLO EXPERIENCE REPORT - CREW STATION INTEGRATION

Volume I - Crew Station Design and Development

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16. Abstract

An overview of the evolution of the design and development of the Apollo command module and lunar module crew stations is given, with emphasis placed on the period from 1964 to 1969. The organizational planning, engineering techniques, and documentation involved are described, and a detailed chronology of the meetings, reviews, and exercises is presented. Crew station anomalies for the Apollo 7 to 11 missions are discussed, and recommendations for the solution of recurring problems of crew station acoustics, instrument glass failure, and caution and warning system performance are presented. Photographs of the various crew station configurations are also provided.

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APOLLO EXPERIENCE REPORT

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This technical note documents experience gained in the area of spacecraft crew station design and operations during the Apollo Program. Emphasis is given to the time period ranging from early 1964 up to, and including, the Apollo 11 lunar-landing mission of July 1969 – an era that covers three important phases of the Apollo Program: the design phase, hardware construction, and mission operations.

This technical note consists of five volumes. Volume I, "Crew Station Design and Development, " gives an overview of the total crew station integration task. Volumes II, III, IV, and V are specialized volumes, each of which is devoted to a basic functional area within the Apollo crew station. The subject of each volume is indicated by its title, as follows.

Volume II, "Crew Station Displays and Controls," NASA TN D-7919

Volume III, "Spacecraft Hand Controller Development," NASA TN D-7884

Volume IV, "Stowage and the Support Team Concept," NASA TN D-7434

Volume V, "Lighting Considerations," NASA TN D-7290

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ACRONYMS

ACA	attitude control assembly
AGS	abort guidance system
AOH	Apollo Operations Handbook
AOT	alinement optical telescope
ASPO	Apollo Spacecraft Program Office
CARR	customer acceptance readiness review
CCFF	crew compartment fit and function
CDR	commander
CFE	contractor-furnished equipment
CM	command module
CMC	command module computer
CMP	command module pilot
COAS	crew optical alinement sight
CSM	command and service module
C&W	caution and warning
DEDA	data entry and display assembly
DSKY	display and keyboard
EASEP	early Apollo scientific experiments package
ECS	environmental control system
E&D	engineering and development
EL	electroluminescent
EMS	entry monitor system

EMU	extravehicular mobility unit
EOR	Earth orbit rendezvous
EVA	extravehicular activity
FCST	flightcrew support team
FDAI	flight director attitude indicator
FEAT	full engineering and analysis test
GDA	gimbal drive actuator
GDC	gyro display coupler
GFE	Government-furnished equipment
G&N	guidance and navigation
GN&C	guidance, navigation, and control
IFTS	in-flight test system
JSC	Lyndon B. Johnson Space Center
KSC	John F. Kennedy Space Center
KSC-E	KSC egress trainer
LEB	lower equipment bay
LGC	lunar module guidance computer
LiOH	lithium hydroxide
LM	lunar module
LMP	lunar module pilot
LOR	lunar orbit rendezvous
LPD	landing-point designator
LTA	lunar module test article

MESA	modular equipment stowage assembly
MDC	main display console
MSC	Manned Spacecraft Center
PGA	pressure garment assembly
PGNS	primary guidance and navigation system
PLSS	portable life-support system
PTT	push-to-talk
PUGS	propellant utilization and gaging system
RCS	reaction control system
R&D	research and development
RFC	request for change
RHC	rotational hand controller
RID	review item disposition
RR	rendezvous radar
SC	spacecraft
SCS	stabilization and control system
SI	Système International d'Unités
SM	service module
vhf	very high frequency
WIF	water immersion facility

APOLLO EXPERIENCE REPORT

CREW STATION INTEGRATION

VOLUME I – CREW STATION DESIGN AND DEVELOPMENT

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SUMMARY

Because of previous spacecraft design experience, the Apollo command module and lunar module were designed for operation with full use of human capabilities. As a result, automatic systems were used primarily to enhance crew safety or mission performance. The flight stations were equipped and arranged to reflect the onboard command and control responsibilities of each crewman. Secondary crew stations were provided in both vehicles for donning and doffing extravehicular support equipment, for guidance and navigation optical alinement operations, and for crew resting.

The development cycle for the Apollo crew stations (and associated equipment) was similar to that of other aerospace programs: basic requirements were generated, a full-scale mockup or working model was developed, procedures for using the equipment were developed, equipment and procedures were evaluated through simulation, and design and procedures were modified as required. Critical and complex crew station equipment and operations were evaluated under representative environmental conditions – within lighting mockups, vacuum test chambers, drop test vehicles, centrifuge modules, water immersion facilities, and variable-g aircraft.

Literally thousands of multilevel design and operation exercises and reviews held before the Apollo missions resulted in many improvements and refinements to crew station design and operations. Consequently, relatively few crew station anomalies were experienced during actual flight operations, and those that occurred during the first five manned Apollo missions (Apollo 7 to 11) were unique and nongeneric.

The success of the Apollo crew station effort was attributable to four basic factors: (1) the use of knowledge gained from prior aerospace experience and practices; (2) the study, review, and simulation of new state-of-the-art designs and operations; (3) the ability to control the many physical and operational interfaces that existed; and (4) the effective communications and information dissemination between program organizational elements. Crew station specification documents delineating generic methodologies and requirements that evolved during the Apollo Program have been prepared for use in subsequent programs.

INTRODUCTION

This volume of the crew station integration series presents an overview of the Apollo crew station design and development efforts as well as the engineering approaches used to integrate the many physical and operational interfaces that existed in the Apollo spacecraft. The crew station design and development effort will be discussed in a quasi-chronological, quasi-subjective manner. The more specialized areas of the Apollo crew stations are not discussed in detail in this document. Individuals who require further detail or additional information about the Apollo crew station configurations or experience are referred to the succeeding volumes of this series and to other crew-station-related Apollo experience reports.

The first section of this report addresses the period of spacecraft evolution between late 1959 and late 1962, during which a baseline definition of the functional and operational requirements for the command module (CM) and lunar module (LM) crew stations was determined.

The second and third sections concern, respectively, the refined crew station requirements, which were applied to the spacecraft design, and the spacecraft configurations that resulted.

The fourth section presents the aspects of methodology, including the relevancy of pre-Apollo experience, and describes engineering tools and techniques; documentation and operational plans; spacecraft and crew integration plans; meetings, reviews, and exercises; and the organizational approach.

The fifth section is a chronological synopsis of selective events that occurred during the design and development of the Apollo CM and LM crew compartments. The intent is to give a representative sampling of significant events that illustrate the application of the engineering requirements and methodology discussed in earlier sections.

The last section of the report is a discussion of the in-flight experience during the Apollo 7 to 11 missions that concerned crew station equipment.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Systême International d'Unitês (SI). The SI units are written first, and the original units are written parenthetically thereafter.

SPACECRAFT EVOLUTION

In the latter part of 1959, NASA began planning the development of advanced manned spacecraft systems. Primary efforts included (1) the preliminary design of a multiman spacecraft for a circumlunar mission, with particular attention given to using the capsule as a temporary space laboratory, lunar-landing cabin, and deep-space probe; (2) mission analysis studies to establish exit and reentry corridors, weights, and propulsion requirements; and (3) test program planning to determine the number and purpose of the missions to be flown.

These early efforts, coupled with a later (1961) national commitment to accomplish a lunar landing within the decade, ultimately led to an initial definition of the Apollo Program and the establishment of baseline requirements for the Apollo vehicle. As described in the Apollo Spacecraft Statement of Work of July 28, 1961, the program would consist of three phases: phase A would be composed of manned low-altitude Earth-orbital flights lasting as long as 2 weeks and unmanned reentry flights from superorbital velocities; phase B would consist of circumlunar, lunar-orbital, and parabolic-reentry test flights; and phase C would include manned lunar-landing-and-return missions (using either the NOVA-class or Saturn C-3 launch vehicles). The 1961 statement of work included the following requirements for the Apollo spacecraft.

1. Onboard control and monitoring of translunar spacecraft injection for direct ascent and for spacecraft injection from an Earth parking orbit

2. Rendezvous and docking with a space laboratory module or other space vehicle

3. Attitude control for lunar landings and lift-offs and for entering and leaving lunar orbit

4. A single-engine service module (SM) propulsion system that would supply abort propulsion after jettison of the launch escape system, all major velocity increments and midcourse velocity corrections for missions before the lunar-landing attempt, and lunar launch propulsion and transearth midcourse velocity corrections

5. A station for the commander (CDR) in the left or center couch (Duties of the CDR would include control of the spacecraft in manual or automatic modes during all mission phases; selection, implementation, and monitoring of the guidance and navigation (G&N) modes; and monitoring and control of key areas of all systems during time-critical periods.)

6. A station for the copilot (later designated as the command module pilot (CMP)) in the left or center couch (Duties of the CMP would include supporting the CDR as alternative pilot or navigator and monitoring certain key parameters of the spacecraft and propulsion systems during critical mission phases.)

7. A station for the systems engineer (later designated as the lunar module pilot (LMP)) in the right-hand couch (Duties would include responsibility for all systems operations, serving as primary monitor of propulsion systems during critical mission phases, and responsibility for systems placed onboard primarily for evaluation of later spacecraft.)

8. Arrangements of displays and controls to reflect the duties of each crewman (This arrangement would be such that a single crewman could return the spacecraft safely to Earth; all crewmen would be cross trained so that each could assume the duties of the others.)

9. The provision, for each crewman, of a couch and restraint system that would give full body and head support during all normal and emergency acceleration conditions

10. The provision of shirt-sleeve garments, lightweight caps, and exercise and recreation equipment for the crewmen

The statement of work also delineated requirements for a lunar-landing module, which at that time was envisioned as a third propulsion module equipped with landing gear and other apparatus for lowering the command and service module (CSM) to the lunar surface. The propulsion system for the lunar-landing module would be a composite propulsion system consisting of multiple lunar-retrograde engines for the gross velocity increments required for lunar orbiting and lunar landing and a lunar-landing engine for velocity vector control, midcourse velocity control, and the lunar hover and touchdown maneuver.

In December 1961, a contract was awarded for the design and development of the CM and SM, the spacecraft adapter, associated ground support equipment, and spacecraft integration. The following month, preliminary layout drawings were initiated to define the elements of the CM configuration. Additional requirements and limitations imposed on the CM design at this time included a reduction in diameter, a paraglider compatibility for landing (eventually deleted), 113 kilograms (250 pounds) of radiation-protection water (later deleted), redundant propellant tankage for the attitude control system, and an increase in system weight and volume. After drawings depicting the location and orientation of the CM crew and equipment were prepared, engineering orders were released for the construction of Apollo CM and SM full-scale mockups (fig. 1).

At this time, the CM and SM were being designed to support three approaches to the lunar-landing mission: Earth orbit rendezvous (EOR), direct ascent (by use of a NOVA-class launch vehicle), and lunar orbit rendezvous (LOR). The lunar-landing techniques and possible CSM schemes for supporting these approaches are illustrated in figure 2. The advantages of the "dark horse" LOR approach became more apparent as design studies matured. The EOR approach involved the use of an unmanned module to decelerate the CM and SM for descent to the lunar surface. Service-module engine power would be used for lunar ascent and transearth maneuvers. The LOR approach, on the other hand, involved the use of a second manned module for independent descension to and ascension from the lunar surface from lunar orbit. The CSM would remain in lunar orbit for eventual rendezvous and docking with the returning LM.

In the spring of 1962, during a meeting held at NASA Headquarters and attended by representatives from various NASA offices, the LOR technique was selected as the mission mode for the Apollo Program. Additional decisions reached at this meeting included the following.

1. The current concepts of the Apollo CM and SM would not be altered.

2. A lunar excursion vehicle (subsequently called the LM) would be aft of the SM and in front of the Saturn IVB stage. (Procedures and mechanization for the linkup of the CM and LM would require further study.)

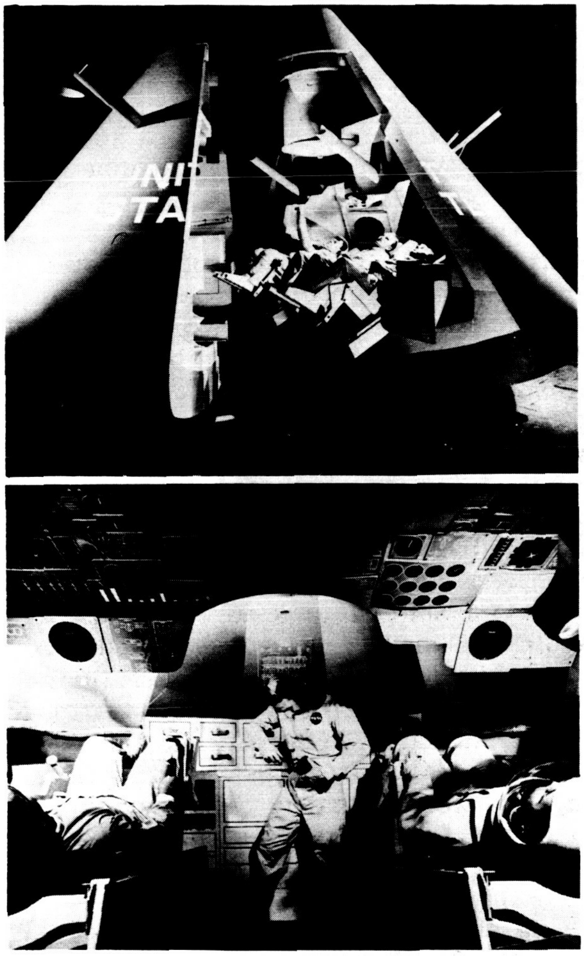

Figure 1.- Two views of CM mockup, circa 1962.

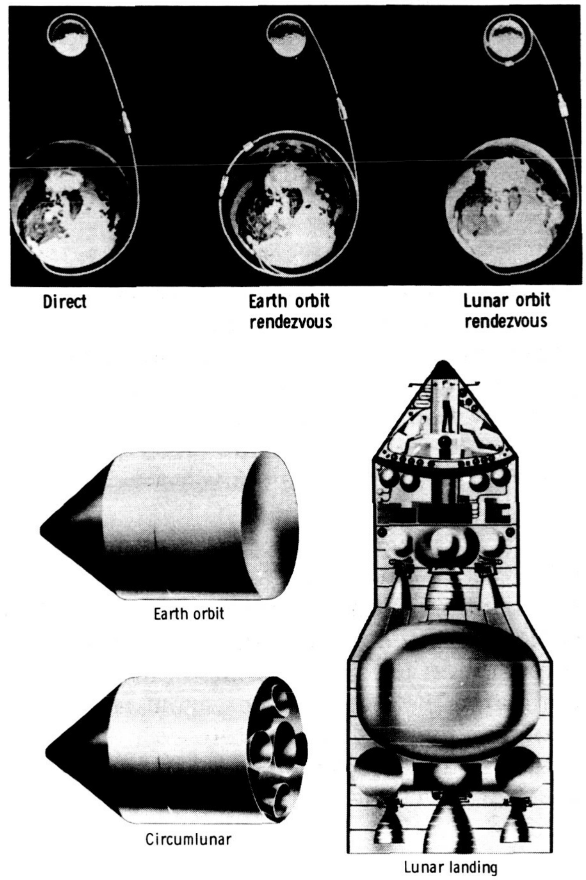

Figure 2.- Concepts of lunar-landing flight techniques and spacecraft configurations for the Apollo Program, circa 1962.

3. For crew safety, an escape tower would be used during launch.

4. Two crewmen would occupy the LM, which would descend to the lunar surface, and both men would be able to leave the LM at the same time.

5. The LM would have a pressurized cabin capable of being maintained for 1 week, even though a normal LOR mission would last only 24 hours.

In July 1962, the newly established Manned Spacecraft Center (MSC) (now the NASA Lyndon B. Johnson Space Center (JSC)) distributed a statement of work for the LM to prospective bidders. Key contractor responsibilities included the detail design and manufacture of the LM and related test articles, mockups, and other hardware with the exception of certain Government-furnished equipment (GFE) such as the G&N system (except the rendezvous radar and radar altimeter), the flight research and instrumentation system, the scientific instrumentation system, and certain components of the crew equipment system (space suit, portable life-support system (PLSS), and

personal radiation dosimeter). The contractor responsibilities also included the integration of GFE into the LM; development of specifications for equipment performance, interfaces, and design environment; and maintenance of interface control documentation with respect to validity and currency. Additionally, the statement of work delineated the following operational requirements for the LM.

1. Before the first translunar midcourse correction, the LM would be transferred from the stowed position in the spacecraft adapter to a docked configuration with the CSM. At a later time in the mission, the two-man LM crew would enter the LM from the CSM through a hatch without being exposed to the space environment. Another hatch would allow access to the LM during countdown and egress into space when the LM was docked with the CSM.

2. The LM systems were to operate at their normal design performance level for 2 days without resupply. Equipment normally operated in the pressurized LM cabin environment would be designed to function for a minimum of 2 days in vacuum without failure. The LM pressurization system would be designed to accomplish six complete cabin repressurizations and to accommodate a continuous leak rate as high as 0.09 kg/hr (0.2 lb/hr). Provision would be made for six recharges of the PLSS, which had a normal operating time of 4 hours without resupply. Under usual conditions in the LM cabin, the crew would wear unpressurized space suits. Either crewman would be able to return the LM to the CSM and successfully perform the rendezvous and the docking maneuver.

3. The LM would be capable of independent separation from the CSM; lunar descent, landing, and ascent; and rendezvous and docking with the CSM. The LM would allow for crew exploration in the vicinity of lunar touchdown but would not be required to have lunar surface mobility. Lunar landing would be attempted from a lunar orbit height of 185 kilometers (100 nautical miles). After separation, the LM would transfer from the circular orbit to an equal-period elliptical orbit that would not intersect the lunar surface. The hovering, final touchdown maneuvers, and landing would be performed after the LM achieved the elliptical orbit. Normally, there would not be a requirement to reposition the LM attitude before lunar launch. After lunar launch, the LM would be transferred from an elliptical to a circular orbit before rendezvous and docking with the CSM. The LM would not be recoverable.

Baseline requirements for the LM crew station were also delineated in the statement of work. The flightcrew would consist of the CDR and the LMP, and the crew station equipment would include adjustable seats, food and water, first-aid equipment, space suits, a PLSS for each crewman, and personal radiation dosimeters.

As with the CM, specifications of crew size, crew equipment, spacecraft systems, and mission technique for the LM resulted in improved spacecraft volumetric definition. Because the LM would be operated only in space, aerodynamic streamlining was not required. The absence of this requirement was responsible for the radically different shape of the LM, compared to that of the CM. Relief from the aerodynamic constraint also added flexibility to the packaging of the LM and therefore to the layout of the crew station area. One of the prime constraints affecting the exterior and interior design of both the LM and the CM was weight. The Apollo spacecraft weights had been apportioned within an assumed 41 000-kilogram (90 000 pound) limit –

a 4300-kilogram (9500 pound) CM and an 11 600-kilogram (25 500 pound) LM. In the years that followed, weight growth was a continuous problem, especially for the LM. The problem became so severe that certain flight instruments were deleted from the LM, and at one point the lunar surface television camera was seriously considered for deletion.

In November 1962, a contract was awarded for the design and development of the LM. The following year, a full-scale LM mockup was constructed that contained a crew station built and outfitted to comply with the program requirements. A model of the LM (circa 1962) is illustrated in figure 3. By the end of 1962, basic mission and crew station operations had been defined, basic spacecraft and crew equipment had been identified, and the external and internal geometries of the CM and the LM had evolved to configurations not radically different from those of the "as flown" spacecraft (figs. 4 to 6).

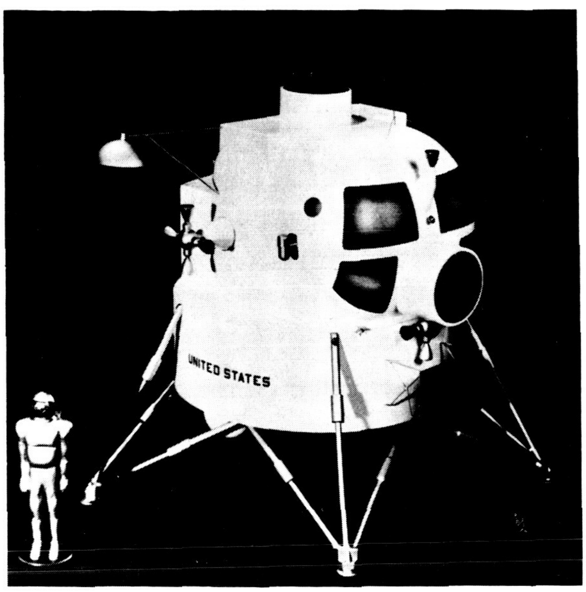

Figure 3.- A model of the LM, circa 1962.

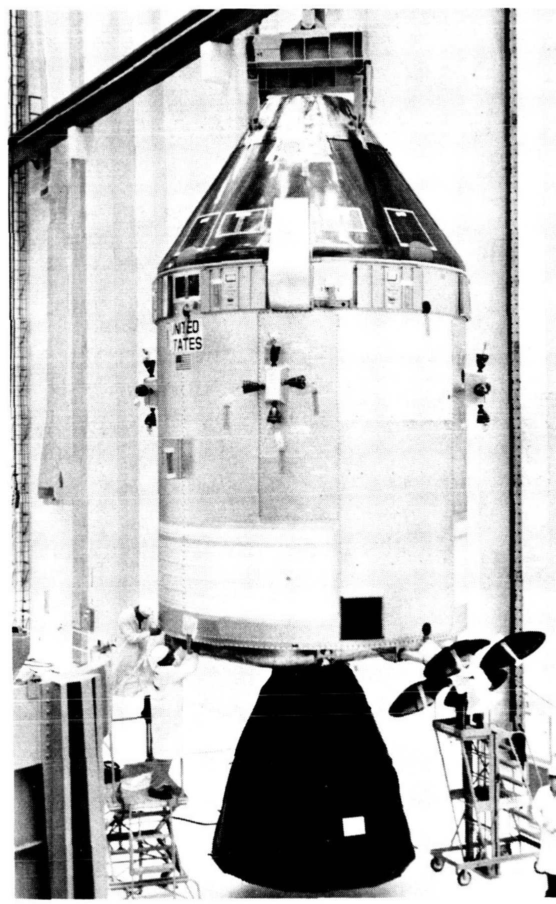

Figure 4.- The Apollo CSM, circa 1969.

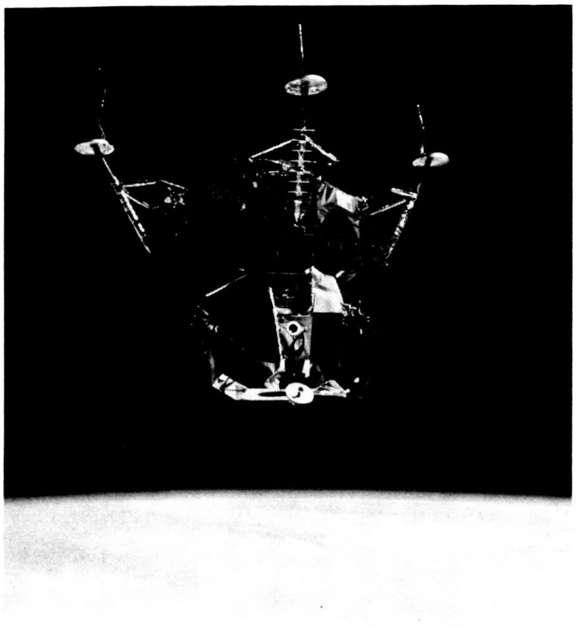

Figure 5. - The Apollo 9 LM.

Figure 6. - The Apollo 9 CM and LM in the docked configuration.

CREW STATION REQUIREMENTS

The CM and LM were designed for operation with full use of human capabilities. The spacecraft were designed to normally use inputs from Earth-based tracking and computing facilities in conjunction with the onboard systems; however, the CM and the LM were both provided with the capability of performing critical mission operations independent of ground facilities. Fundamental crew station requirements were as follows.

1. Maintenance: In-flight maintenance shall not be performed on the vehicle subsystems.

2. Crew control: The flightcrew shall have the capability of controlling the vehicles throughout all flight modes. The crew shall initiate all abort modes when automatic systems are not required to ensure crew safety.

3. Automation: Automatic systems shall be used only to enhance the performance of the mission. Manual overrides of automatic systems shall be provided where possible.

4. Safety: The design of the spacecraft and equipment shall minimize the possibility of crew injury. Fire, explosion, toxicity, failure mode effects, and failure propagation shall be primary considerations.

5. Single crewman operation: The CM and LM shall be designed to allow for operation by a single crewman in a contingency situation.

6. Anthropometry: The vehicle design shall accommodate crewmen between the 10th and 90th percentile for the following dimensions: weight, standing height, sitting height (erect), buttock-to-knee length, knee height (sitting), hip breadth (sitting), shoulder breadth (bideltoid), and arm reach from wall. Other body dimensions shall fall within the 5th and 95th percentiles as defined by WDAC-TR-52-321.

7. Docking: The spacecraft subsystems shall be designed to accommodate the two docking operations and the separation operation required for the lunar-landing mission. With the spacecraft in the docked configuration, an unaided crewman, in a pressurized or unpressurized suit, shall be capable of performing all the functions necessary to accomplish intervehicular crew and equipment transfer in either direction.

8. Extravehicular crew transfer: Handrails, restraints, and exterior lighting shall be provided to permit the extravehicular transfer of crewmen and scientific payloads between the vehicles, in a contingency mode.

9. Crew station environment: The vehicles shall be designed with an environmental control system (ECS) that provides a normal shirt-sleeve environment: an oxygen pressure of 35 kN/m^2 (5 psia), a temperature of 297 K (75° F), and a relative humidity of 40 to 70 percent. Provisions shall be included for planned or contingency pressure-suit operations, thermal control of equipment, PLSS charging, and pressurization of the CM-LM tunnel and the LM.

10. Cabin arrangement: The cabin arrangement shall provide for the effective performance of crew tasks and the efficient stowage of associated equipment and expendables. The flight stations shall reflect the onboard command and control responsibilities of the crew and provide for active onboard management of the vehicle subsystems. Secondary crew stations shall be provided for the donning and doffing of extravehicular support equipment, for G&N operations such as optical alinement, and for crew resting.

11. Support and restraint: Crew support and restraint shall be provided to protect the crew and to enable the performance of all tasks associated with either a nominal or an aborted mission. The crew shall be restrained during the powered portions of the flight and during zero-g conditions, principally to counteract the forces generated by crew mobility. Supports and restraints shall contribute minimum interference with the operation of and access to the controls and displays and shall not limit window use for external visibility.

12. External visibility: Windows shall be provided primarily for aiding in lunar landing, docking, and general navigation.

13. Crew station lighting: Internal and external lighting shall be provided to permit the performance of all crew tasks. Control and display panel illumination shall be adjustable to compensate for varying ambient light conditions and to ensure retention of crew visual adaptation. Lighting shall be provided for crew use in illuminating remote or shadowed areas of the crew cabin.

14. External lighting: External lights shall be provided as visual aids in support of the rendezvous and docking maneuver (visual acquisition, attitude determination, and docking alinement).

15. Displays and controls: The vehicles shall be provided with displays and controls that enable the flightcrew to control and monitor relevant aspects of mission-related phenomena.

CM AND LM CREW STATION CONFIGURATIONS

The Apollo 11 crew station configurations are discussed briefly in the following paragraphs. More detailed information is given in the succeeding volumes of this report, other crew-station-related Apollo experience reports, and the Apollo Operations Handbook (AOH). The CM and LM configurations are discussed concurrently in the following paragraphs to emphasize the similarity in the basic types of equipment used in both crew stations. The exterior spacecraft configurations are briefly described so that the relationship between internal and external geometries and equipment may be established.

Vehicle Exteriors

The exterior configurations of the CM and LM are illustrated in figures 4 to 6. The conical-shaped CM was approximately 3.4 meters (11 feet) in height and 3.7 meters (12 feet) in diameter. By comparison, the box-shaped ascent stage of the LM was approximately 2.7 meters (9 feet) in height and 4.3 meters (14 feet) in breadth. The substantial breadth of the LM was primarily attributable to the added volume required for consumables tankage; the bulk of CSM consumables was contained in the SM. The LM was equipped with an external platform approximately 0.9 meter (3 feet) square, below the forward hatch, which provided the crewmen with workspace for handling equipment during lunar surface extravehicular activity (EVA) and aided LM ingress and egress.

Crew Compartments

Major equipment contained within the crew compartments of the CM (figs. 7 to 14) and the LM (figs. 15 to 22) included controls and displays for the operation of the spacecraft and spacecraft systems, restraint harness assemblies, window shades, crew equipment, food and water, and waste management provisions. Survival equipment and couches also were provided in the CM. The CM had an interior volume of 10.4 cubic meters (366 cubic feet). Interior bays, lockers, couches, and crewmen accounted for 4.4 cubic meters (156 cubic feet); therefore, a total free volume of 6 cubic meters (210 cubic feet), or 2 cubic meters (70 cubic feet) per crewman, remained. The total interior volume of the LM crew compartment was 7 cubic meters (235 cubic feet). Approximately two-thirds of this volume was in the 2.3-meter (92 inch) diameter forward cabin section, with the remaining volume in the 1.4-meter (54 inch) midsection. The LM volumetric values closely approximate two-thirds of the values specified for the

CM (two-man as opposed to three-man occupancy). Total free volume was therefore approximately 4 cubic meters (140 cubic feet).

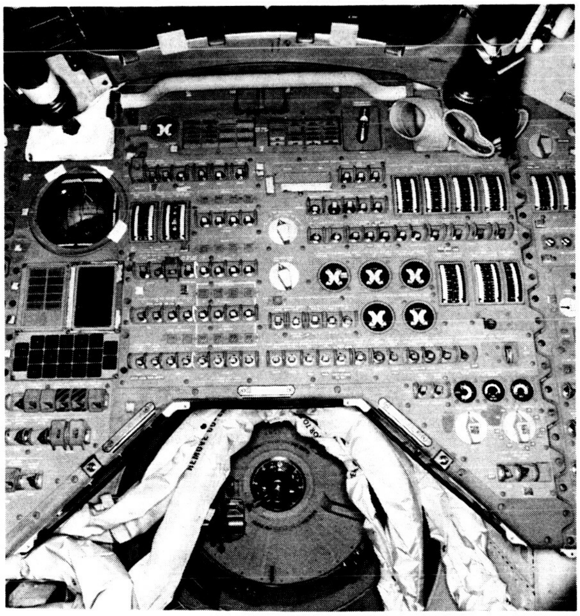

Figure 7. - The CM interior – looking forward toward tunnel.

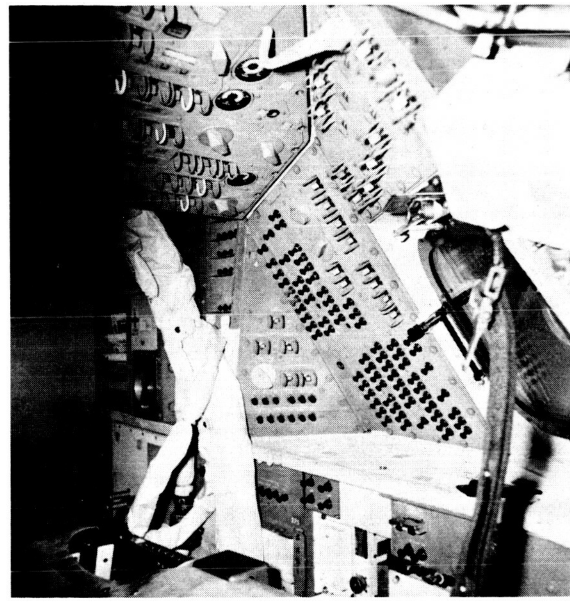

Figure 9. - The CM interior – looking right and outboard.

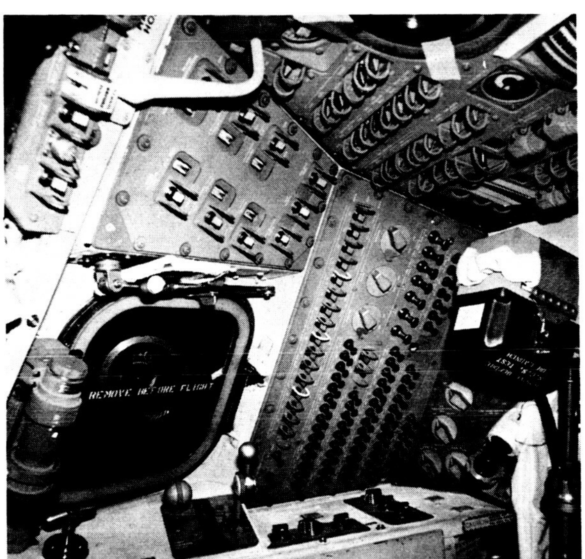

Figure 8. - The CM interior – looking left and outboard.

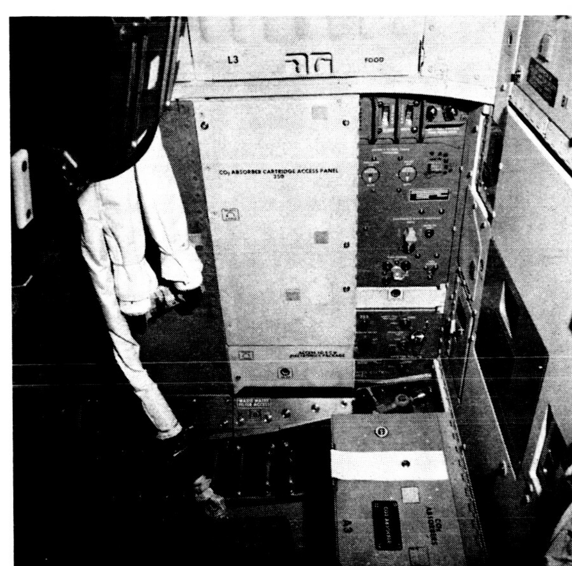

Figure 10. - The CM interior – left-hand equipment bay (ECS equipment area).

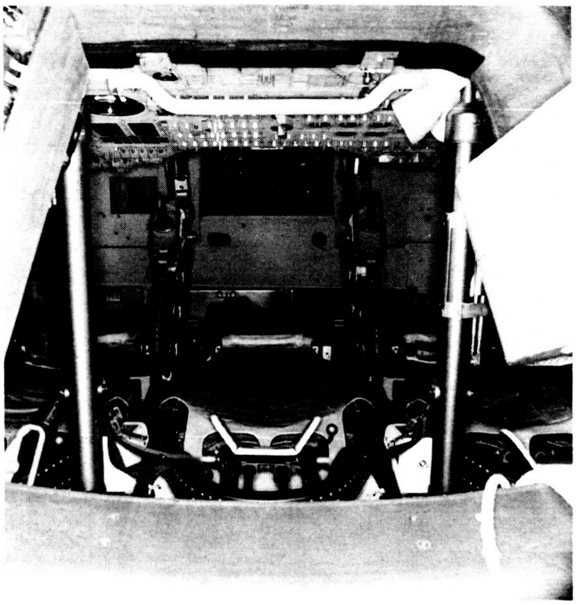

Figure 11. - The CM interior – lower equipment bay (guidance, navigation, and control equipment location).

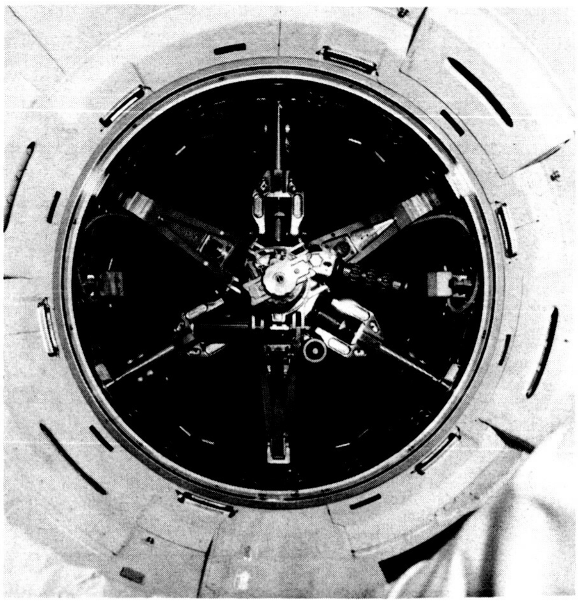

Figure 13. - The CM interior – hatch removed and probe installed.

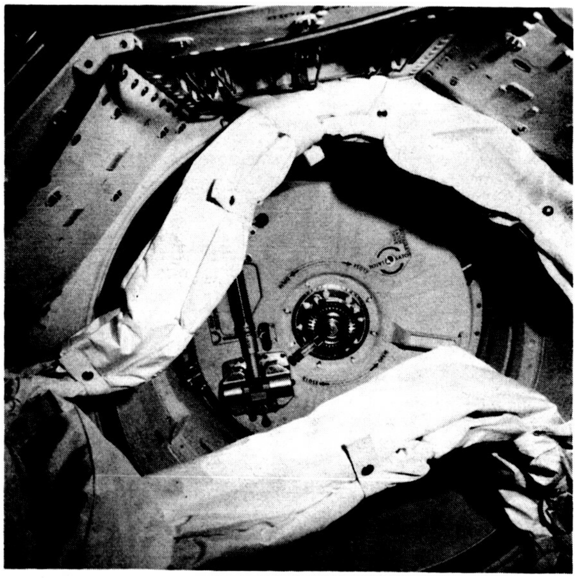

Figure 12. - The CM interior – tunnel area with hatch installed.

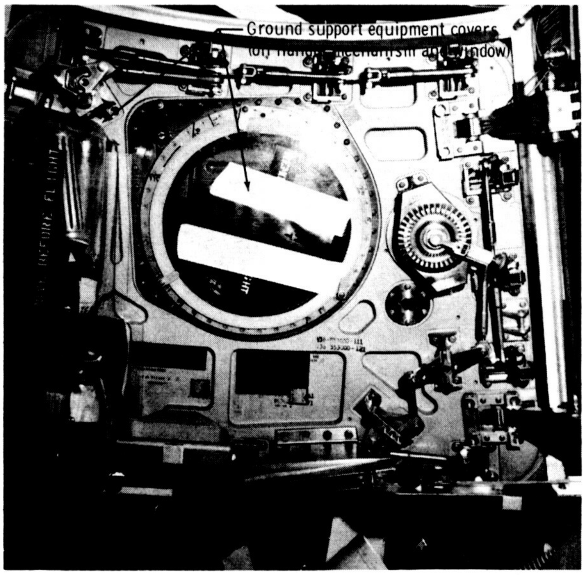

Figure 14. - The CM interior – side hatch in full-open position.

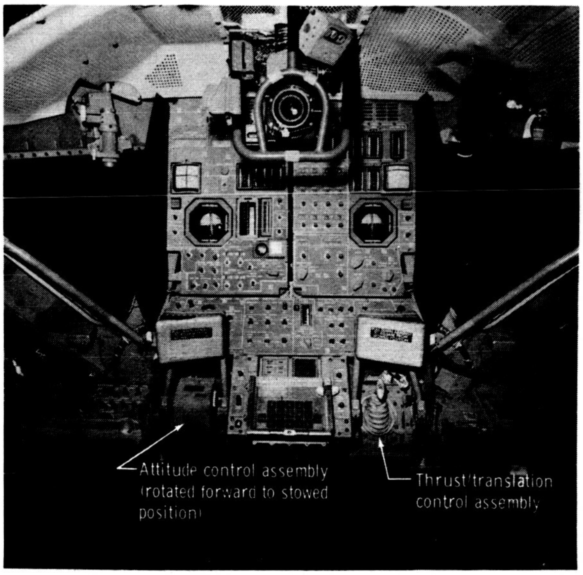

Figure 15.- The LM interior – forward section.

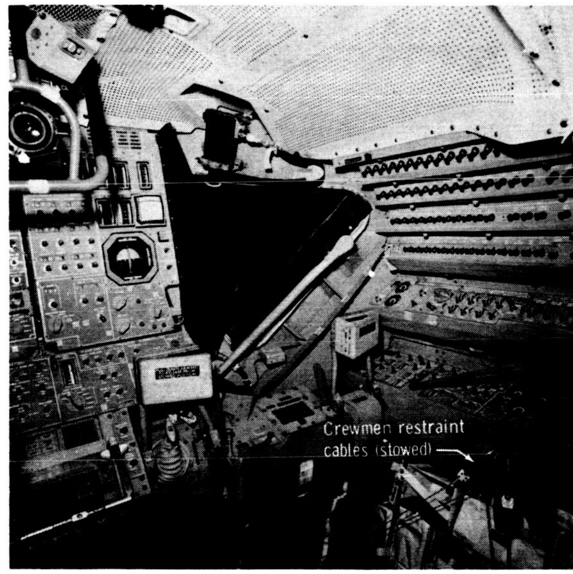

Figure 17.- The LM interior – looking right and outboard.

Figure 16.- The LM interior – looking left and outboard.

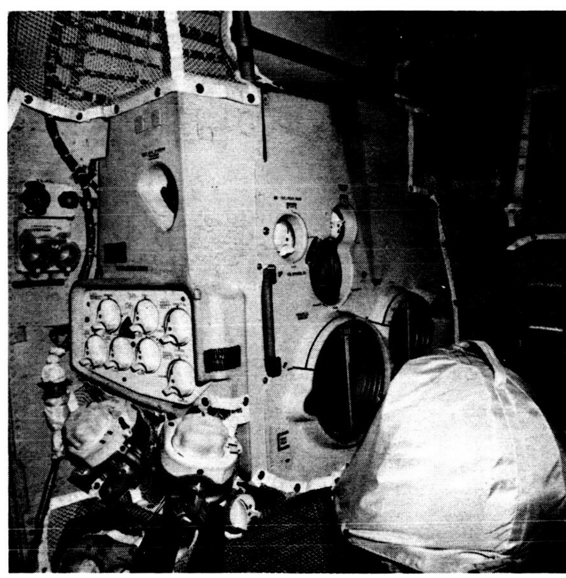

Figure 18.- The LM interior – looking aft and left (ECS equipment location).

Figure 19. - The LM interior – looking aft and right (stowed equipment area).

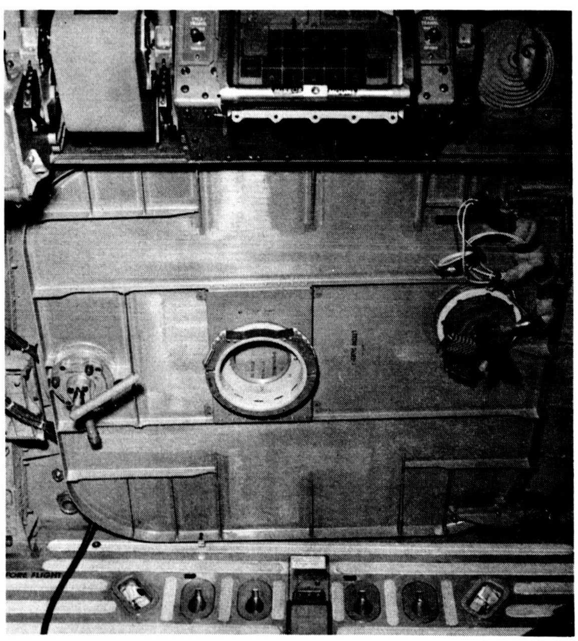

Figure 20. - The LM interior – forward hatch.

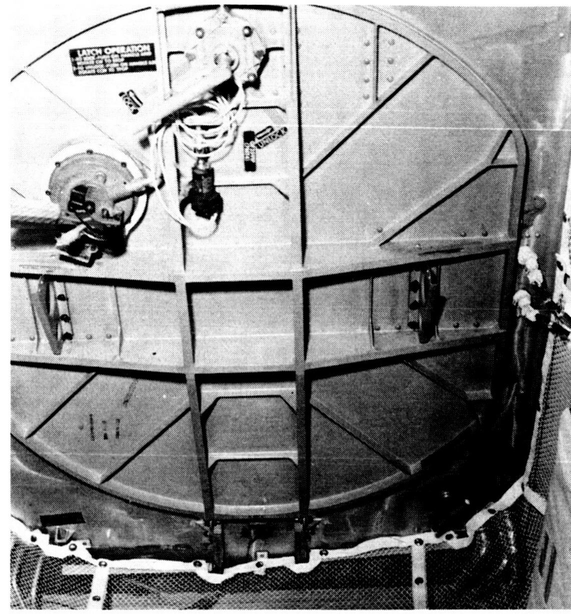

Figure 21. - The LM interior – overhead hatch.

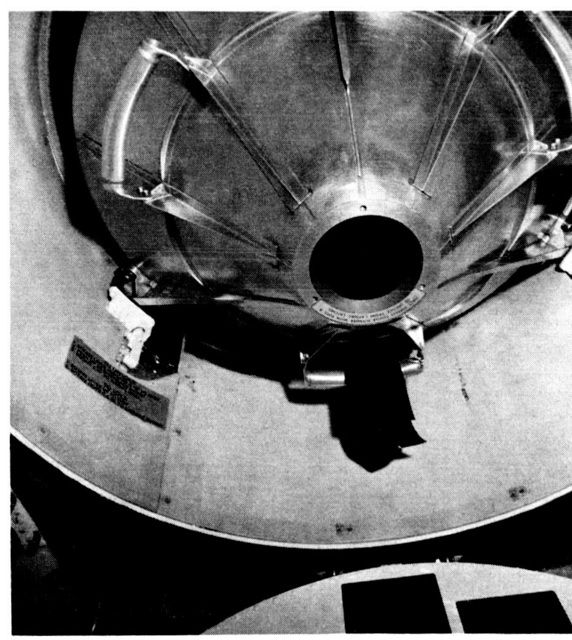

Figure 22. - The LM interior – overhead hatch open and drogue installed.

Both vehicles were equipped with docking tunnels for the transfer of crewmen and equipment between the CM and the LM. The tunnels were sized to allow passage of a crewman in a pressurized suit with an attached extravehicular mobility unit (EMU). In each vehicle, access to the tunnel area was provided by a hatch that could be operated from either side. The geometry of the LM interior enabled the LM hatch to be hinged and rotated into the LM cabin, whereas the CM hatch had to be removed and stowed in the CM cabin to permit tunnel operations. The LM tunnel contained the docking drogue and an electrical umbilical for routing power between the two vehicles. The docking probe was installed in the CM tunnel. To provide for more flexible operations and to safeguard against certain failures, the mechanisms in the probe and drogue were designed to permit removal from either end of the docking tunnel. A second hatch was provided on both vehicles. Side access to or from the CM crew compartment was provided by an outward-opening single integrated hatch assembly. Forward access to or from the LM crew compartment was provided by an inward-opening hatch assembly. To augment ground operations and to provide for contingency flight operations, the cabin relief and dump valves installed in all hatches were designed to be operated from outside as well as inside the crew compartments.

The CM was equipped with two triangular forward-viewing windows, two square side-observation windows, and a round hatch window. Two triangular forward windows in the LM provided visibility during the descent, ascent, and rendezvous and docking phases of the mission. A rectangular window directly above the LM flight station for the CDR provided visibility for the overhead docking maneuvers. The windows in both vehicles were provided with thermal and antireflective coatings and window shades.

Stowage Locations

The numerous loose items of personal and systems equipment in the CM and the LM were stowed in compartments, lockers, and bags (figs. 7 to 22). Stowage compartments were built into the interior walls of both the CM and the LM. Equipment was placed in "cushions" and inserted into these compartments. Removable aluminum lockers with preinstalled cushions also were used in both vehicles. The stowage compartment and locker doors had retention mechanisms that could be actuated with one hand (an aid in zero-g operations). A variety of stowage bags also was used in both vehicles. The stowage containers were labeled for identification and as a location aid. In the CM, containers were numbered consecutively from fore to aft; the numbers were prefixed with a letter designator of the bay. For example, right-hand equipment bay compartments were labeled R1 to R13. In the LM, stowage areas and contents were identified by descriptive labels. Letter designators were not necessary in the LM because the number of stowage items and configurations was considerably less than that in the CM.

Couches and Restraints

The CM was equipped with couches qualified to support the crew during normal and contingency accelerations as high as 30g forward or aft ($\pm X$), 18g up or down ($\pm Z$), and 15g laterally ($\pm Y$). Each couch consisted of a headrest-equipped body support with back pan, seat pan, leg pan, and foot pan. Body support was accomplished by a web of Armalon (multiple layers of fiberglass Beta cloth impregnated and covered with Teflon)

over the support frame. In the CM, the individual flight restraint harnesses for the crewmen were attached to the crew couches. Each harness consisted of a lapbelt and two shoulder straps that interfaced the lapbelt at the buckle. The lapbelt buckle was a lever-operated, three-point-release mechanism. In the LM, crew support was accomplished by using restraint cables (figs. 16 and 17) attached to waist-high D-rings on the sides of the pressure garment assembly (PGA). A constant-force reel control provided a downward force of approximately 135 newtons (30 pounds). Equipment restraint on the Apollo vehicles was accomplished with a variety of devices; Velcro, utility straps, and bungees were the preferred items. Connections were made by using Velcro, hooks, clips, and snaps.

Displays and Controls

The displays and controls for operation of the CM spacecraft and systems were located throughout the crew compartment (figs. 7 to 14). Primary displays and controls were located on the main display console (MDC), which consisted of 14 subpanels. The flight control displays and controls were concentrated within panels 1 and 2 for access by the CDR or the CMP. The majority of other subsystem controls was distributed in other panel areas that were accessible to the CMP or the LMP. A G&N station, which included an optical sight and a display and keyboard (DSKY) for addressing the Apollo G&N computer, was provided in the lower equipment bay (LEB). The display and control panels in the LM, with the exception of certain ECS items, were located in the forward section of the crew compartment (figs. 15 to 17). Primary displays and controls were situated in the two main display panels, numbers 1 and 2, located directly in front of the CDR and the LMP. Other subsystem displays and controls were distributed among two lower center panels, two bottom side panels, two lower side panels, one center side panel, and two upper side panels. All circuit breakers were installed in the upper side panels located outboard from the CDR and the LMP. An ECS station containing suit plumbing outlets, valve controls, and other ECS items was located in the LM midsection area immediately aft of the LMP (fig. 18). A G&N station, which contained an alinement optical telescope (AOT) with integrated controls, was provided between the flight stations of the CDR and the LMP. A DSKY, visually identical to the two located in the CM, was located in the panel area directly beneath the AOT.

Hand Controllers

Two three-axis pistol-grip hand controllers were provided in each vehicle for commanding attitude changes (figs. 11 and 15). Pitch commands were implemented by motions about a palm-centered axis, yaw commands were implemented by motions about the grip longitudinal axis, and roll commands were effected by a left-right motion. The LM attitude control assemblies were also used in an incremental landing-point designator (LPD) mode during the final approach phase of the lunar landing. In this mode, the angular error between the designated landing site and the desired landing site was nulled by repetitive manipulation of an attitude control assembly (ACA). The LPD signals from the ACA were directed to the LM guidance computer (LGC), which issued commands to move from the designated landing site incrementally along the lateral and longitudinal axes. Angular information was obtained by using the vertical and horizontal scales of the LPD on the left forward window.

By using reaction control system (RCS) thrusters, the translation hand controllers in the CM and LM provided the means to accelerate the spacecraft manually along one or more of its axes (figs. 11 and 15). These controllers were mounted with their axes approximately parallel to those of the spacecraft, and the direction of movement was pilot oriented. The single internally redundant controller in the CM also provided two special functions: clockwise movement of the T-shaped handle transferred spacecraft control from the command module computer (CMC) to the stabilization and control system (SCS), and counterclockwise movement provided manual abort initiation during the launch phase, if necessary. The LM controllers were dual-purpose devices in that they also enabled a manual throttling control of the descent engine. Moving a throttle-jets lever to the throttle position permitted an LM crewman to increase or decrease the magnitude of the descent engine thrust by an up or down movement, respectively, of the controller.

Lighting

Exterior and interior lighting equipment on the Apollo vehicles aided in the performance of crew visual tasks. The interior lighting systems provided general cabin illumination, as well as displays and controls illumination. Fluorescent lamps provided floodlighting of CM interior work areas, and incandescent lamps were used in the LM. Integral panel and numerics lighting was provided in both vehicles by electroluminescent (EL) materials. High-intensity signal lights and tunnel lights were incandescent. Pen flashlights were used for supplementary lighting of difficult access areas. Utility lights also were provided in the LM as backup to the prime cabin floodlighting system. In the CM, a dual-powered/dual-filament design was used in the floodlighting systems to provide a redundancy capability. The exterior lighting systems enabled the Apollo crews to visually guide and orient the LM and CSM to achieve successful tracking and docking. Exterior lighting on the CM consisted of a docking spotlight, eight running lights for orientation, a docking target (mounted inside the right-hand rendezvous window), an EVA floodlight, and a rendezvous beacon. Exterior lighting on the LM consisted of a radioluminescent docking target, five docking lights for orientation, and a high-intensity tracking light.

Optical Equipment and Aids

Several optical devices and aids were provided on the Apollo vehicles in addition to the G&N optical sights. Items used included a crew optical alinement sight (COAS), window markings, CM internal viewing mirrors, and a monocular for lunar survey from the CM. The COAS was similar to an aircraft gunsight and consisted of a collimated reticle with vertical, horizontal, and radial scales. The primary function of the COAS was to provide the LM and CM crewmen with precise information regarding relative angles between the CM and LM during the docking maneuver. The CM COAS could be used in either the left or right rendezvous windows. The LM COAS could be used in either the overhead or left windows.

The left and right rendezvous and hatch windows of the CM were equipped with markings to aid the crew in monitoring the entry maneuver. An LPD scale was scribed onto the left forward window in the LM to aid in monitoring and updating the G&N-computed lunar-landing point. A scribed scale was also provided in the LM overhead

docking window for monitoring vehicle attitude during lunar lift-off, rendezvous, and docking.

Internal viewing mirrors were used in the CM to aid a reclined crewman in buckling and adjusting the restraint harness and in locating couch controls and space-suit connectors. When a crewman was in a pressurized suit and in a reclined position on a CM couch, the lower edge of the MDC blocked normal visibility of these areas.

METHODOLOGY

Relevancy of Pre-Apollo Experience

Many of the design and operational approaches used in the Apollo Program were derived directly from the Gemini Program. A comparison of the Gemini and Apollo crew station configurations (figs. 23 and 24 compared with figs. 7 to 22, respectively) illustrates that state-of-the-art display and control devices such as fly-by-wire hand controllers and computer keyboards were introduced in the Gemini Program and carried over into the Apollo Program. Gemini Program experience also fostered knowledge of crew station concepts in terms of modular stowage, frequency of crew equipment use, zero-g handling procedures, and interface control of equipment. Many of the requirements that were established for Gemini displays and controls and other crew station equipment were applied to Apollo equipment.

An important aspect of the information gained from the Gemini Program originated in the CM and LM design reviews in which the Gemini crews participated. The early Gemini pilots, for example, ascertained that digital rather than analog timers

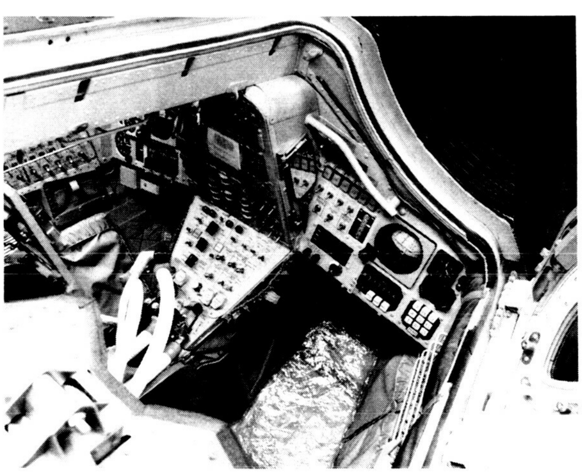

Figure 23. - Gemini spacecraft interior.

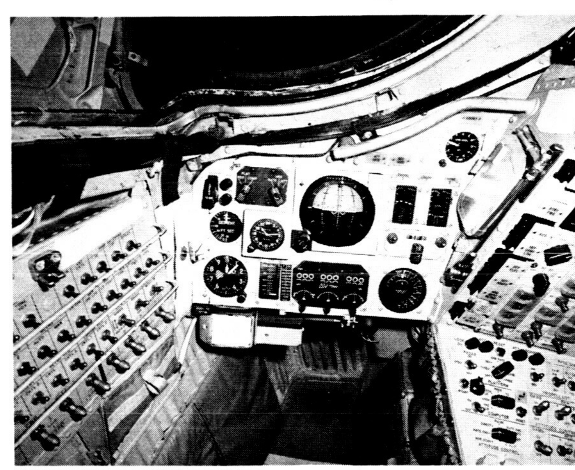

Figure 24. - The command pilot's instrument panels in the Gemini spacecraft.

were essential for performing time-critical spacecraft operations. They also identified a need for a capability to dim the floodlighting of individual crew stations; this dimming would enable out-the-window night viewing for one crewman while another crewman read onboard data. As a result of the Gemini pilot inputs, all subsequent flight stations were equipped with digital timers and individual lighting controls.

Certain elements of Apollo crew station design and operations could not be based on previous aerospace experience. The Gemini Program had demonstrated the feasibility of rendezvous and docking, but the transfer of men and equipment between docked vehicles that was necessary during the Apollo Program had not been attempted. The Gemini Program, as well as Project Mercury, had demonstrated the feasibility of zero-g operations and the need for zero-g restraints, but 1/6-g operations (as on a lunar-landing mission) had not been experienced. Experience from the Gemini Program and Project Mercury had furnished answers to many questions relative to interior and exterior lighting and visibility requirements, but many questions remained unanswered in regard to the near-lunar and lunar-surface lighting environments.

The Apollo crew station integration task was enormously complicated, compared to that of the Gemini Program. The Apollo concept required the design of two distinctly different types of vehicles (the CM and the LM), a design that provided for the transfer of men and equipment between the vehicles, and a design that permitted lunar orbit and lunar surface operations. These factors caused a substantial increase in the number of physical and operational interfaces between the flightcrew and the spacecraft hardware. The Apollo 11 spacecraft (CM and LM) flew with approximately 350 crew station displays, 1100 controls, and 600 types of stowable equipment. Approximately 400 stowage line items were stowed in the CM, and 200 were stowed in the LM. Approximately 50 of these line items were transferred from the CM to the LM before the lunar landing. The Apollo spacecraft contained four times as much equipment as that flown on the Gemini spacecraft, which typically contained approximately 90 displays, 350 controls, and 150 types of stowage equipment.

Engineering Tools and Techniques

Many of the engineering tools and techniques used to develop Apollo crew compartment design and operations were standardized devices and procedures that have been used for most aircraft programs. In fact, some of these tools and techniques have been standardized to the extent that they are delineated within military specifications as mandatory requirements for all military systems, equipment, and facilities, as in Military Specification MIL-H-46855. The standard tools and techniques used for the Apollo effort included the application of human engineering principles and criteria in system engineering analysis; experiments, laboratory tests, and studies required to resolve human engineering and life-support problems specific to the system; construction of three-dimensional full-scale mockups of equipment involving critical human performance; dynamic simulation; application of human engineering principles to equipment detail design drawings, work environment, and facilities design and performance and design specifications; development of procedures for operating, maintaining, or otherwise using the system equipment, based on human performance functions and tasks identified in system engineering and tasks analysis; and integrated man and machine demonstration and certification tests.

Many of the specialized engineering tools and techniques used in Apollo crew station efforts were actually conceived during the Gemini Program and were subsequently improved during the Apollo Program. Included in this category were the variable-g aircraft, used to evaluate crew equipment and operations under zero-g or lunar-g conditions; neutral-buoyancy simulators (water immersion facilities) for zero-g and 1/6-g evaluations; full-size docking simulators and simulations; the use of in-flight photography to evaluate the functioning of crew station equipment in unmanned research and development (R&D) spacecraft; the scheduling of periodic crew/crew-equipment integration and implementation meetings; the preparation and use of a spacecraft/crew integration plan to define the specific participation by flightcrews and flightcrew support teams in spacecraft reviews, testing, and prelaunch operations; the preparation and maintenance of spacecraft stowage drawings; and the periodic scheduling of bench reviews and crew compartment fit and function (CCFF) reviews for crew equipment.

Tools and techniques developed especially for, or which supported, Apollo crew station efforts included an MSC plan for close monitoring and evaluation of the operational aspects of contractor engineering simulation programs by astronauts, flightcrew training personnel, and flightcrew integration personnel; periodic guidance and control implementation meetings; preparation and maintenance of interface control drawings and documents to define and control functional and hardware interfaces between equipment supplied by different parties; use of standardization documents for nomenclature control of crew station displays and controls; generation of a nonmetallic materials document to delineate selection and acceptance guidelines relative to nonmetallic materials and test requirements for the control of flammability and toxicity of nonmetallic materials used in the Apollo spacecraft; and a photographic documentation plan that specified required photography of each individual spacecraft through all stages of manufacturing and testing, including vehicle closeout.

Documentation and Operational Plans

It has been stated that "the enormity of the Apollo-Saturn launch vehicle is only exceeded by the volume of paperwork which was required to build and launch the vehicle." Therefore, enumeration of all the types of data used to develop Apollo crew station design and operations would not be possible (nor desirable) in this report; however, key data will be mentioned briefly.

The documentation and operational plans, in approximate chronological order of development, included top-level mission and vehicle end-item specification documents, which delineated contractual mission and vehicle requirements; a lunar-landing mission design plan, which delineated crew functions, assignments, and tasks for both normal and alternate mission sequences; conceptual crew-station-arrangement drawings; an Apollo subsystem management plan, which defined the responsibilities for the engineering of the Apollo subsystems; a plan of action for close monitoring and evaluation of operational aspects of contractor engineering simulation programs by astronauts and by flightcrew training and integration personnel; equipment specification documents and control drawings; a design reference mission document, which described a single mission and served as a basis for project reporting and continuing spacecraft design and operational studies; an LM spacecraft/crew-interface reduced-gravity test plan; interface control documents, which controlled multiparty physical, functional, and operational interfaces; mission rules documents, which established both general and specific

rules and requirements in regard to total mission operations; a spacecraft/crew integration plan for manned Apollo missions; reports on failure modes and effects analysis; AOH's, which contained detailed information on the individual vehicles, events, and procedures applicable to the scheduled mission; spacecraft stowage lists; dedicated Apollo flight plans, which scheduled spacecraft operations and crew activities for performing specific manned Apollo missions; a nonmetallic materials requirements document, released as a postfire corrective item for increased control on nonmetallic materials used in the crew compartments; a crew procedures control plan, which specified methods to be used to control flightcrew procedures delineated in the Apollo flight plans and procedures documents; and a rigorous crew station photography plan.

Interface control documents and/or drawings were used to define and control functional and hardware interfaces between equipment supplied by CM, LM, and EMU contractors and the Government. More than 200 interface control documents and drawings were required to adequately define the interfaces that existed within and between the spacecraft. This number illustrates the complexity of the crew station integration task.

Mission rules documents established both general and specific rules and requirements in regard to total mission operations. The rules were formulated from the inputs of the principal parties responsible for mission operations.

Spacecraft stowage drawings were developed as a tool to manage the large quantity of equipment carried in the CM and LM crew stations. Spacecraft stowage drawings consisted of a top assembly drawing that was divided into four main categories: (1) a listing of all the loose crew equipment (equipment that a crewman could remove, without tools, from one location and place in another location), (2) a three-dimensional view of the crew equipment arrangement in a modular container, (3) a three-dimensional view of crew equipment arrangement in a spacecraft crew station volume, and (4) a modular container location in the spacecraft.

Spacecraft/Crew Integration Plan

During the Apollo Program, a plan was developed that specifically defined the participation of the primary and backup flightcrews, as well as the flightcrew support team (FCST) assigned to a particular mission, in the Apollo spacecraft reviews, in spacecraft checkout testing, and in prelaunch operations. Flightcrew participation was necessary primarily to verify the spacecraft/crew interface and to ensure the operational acceptability of installed equipment. A secondary purpose was to allow the flightcrew to gain valuable operational experience with flight hardware and to become familiar with specific and unique characteristics of the assigned spacecraft.

As detailed in the spacecraft/crew integration plan for manned Block II Apollo CSM and LM missions, an FCST was assigned to each mission. Each FCST consisted of a team leader, a CSM and an LM crew station engineer, a CSM and an LM spacecraft engineer, and a training coordinator. The FCST provided the assigned flightcrews with both general and specific support in tasks ranging from certification of the official stowage list to evaluation of emergency ingress and egress procedures in the rescue training facilities at the NASA John F. Kennedy Space Center (KSC). Equipment liaison groups and support specialists were also assigned to each flightcrew.

The liaison group assisted the FCST in the integration of flightcrew equipment with the spacecraft to support the Apollo Spacecraft Program Office (ASPO) program schedules. The support specialists provided important supplementary support for each flightcrew and team in areas such as EVA procedures and training, checklist development, and experiment integration.

The integration plan specified that the assigned flightcrew and the associated FCST would participate in spacecraft crew station reviews and spacecraft crew compartment design reviews (preliminary design reviews and configuration design reviews) held for their particular spacecraft. The purpose of crew station reviews was (1) to demonstrate the crew interfaces with the spacecraft equipment and the crew-associated equipment, as well as the equipment-to-spacecraft interfaces, as defined in the interface control documents or drawings and other contractor documents and (2) to allow flightcrew evaluation of the stowage, installation, and use of this equipment with respect to mission objectives, requirements, and time line. These reviews were conducted, as required, at the contractor's facilities, with CM and LM spacecraft mockups and suitable crew equipment mockups or flight-configured equipment. The purpose of the spacecraft crew compartment design reviews was to verify that the specific spacecraft design requirements would provide a spacecraft configuration capable of satisfying the mission objectives for the particular flight.

The integration plan also contained a listing of the detailed checkout specifications, the operational checkout procedures, and the test and checkout procedures requiring flightcrew participation. The flightcrew and/or the FCST was to review the preliminary specifications or procedures for each of the tests in which crew participation was mandatory, and their concurrence was required before signoff. Table I exemplifies the type of crew participation in detailed tests. The CCFF test held at KSC for each vehicle was the key test for certifying the operational configuration of flightcrew equipment. The test was performed to demonstrate (1) that each crew equipment flight item was functionally and physically compatible with the spacecraft in which it was to be used, (2) that all equipment was compatible as a package, and (3) that the stowage provisions were compatible with the mission sequence. For the CCFF test, each spacecraft was powered up to functionally check all electrical interfaces for loose equipment. A functional demonstration of all spacecraft lighting was also performed at that time.

Meetings, Reviews, and Exercises

Literally thousands of meetings, reviews, and exercises were required to develop and integrate Apollo crew station design and operations. The prime crew station meetings, in approximate chronological order, included conceptual design meetings on crew station subsystems (e. g., lighting and displays and controls); LM/CM commonality meetings to explore areas in which commonality might be achieved; Apollo docking interface panel meetings, in which the design trade-offs of various docking schemes were evaluated; Block II CM design definition meetings; MSC mockup requirements meetings; Apollo guidance and control implementation meetings, consisting of the various elements involved in guidance, navigation, and control (GN&C) development (e. g., hardware, software, procedures, simulation, and training personnel; pilots; management; and integration personnel); crew integration systems meetings; spacecraft design integration system meetings; interface control document/drawing meetings; postfire

TABLE I. - CREW PARTICIPATION IN TEST AND CHECKOUT PROCEDURES AT KSC[a]

TCP number	Description	Category	
		Mandatory	Optional
Manned spacecraft operations building			
K-3128	CM-LM mechanical docking	X	
K-0070	Combined systems test		X
[b]K-0048	Emergency egress and simulated altitude run	X	
[b]K-0034	CSM altitude chamber run	X	
K-8241	High-gain antenna checkout and PLSS communications test		X
Vertical assembly building			
K-0005	Integrated systems test		X
K-0004	Electrical mate and interface test		X
K-0006	Plugs-in integrated test		X
Pad			
K-0028	Flight readiness test	X	
K-1222	CSM-LM systems interface test		X
[b]K-5117	Flightcrew countdown	X	
[b]K-0007	Countdown demonstration test/ launch countdown	X	

[a]Spacecraft 106 and subsequent.
[b]Requires suited crew and must be preceded by TCP K-3233 (Crew suiting).

redesign meetings; mockup configuration requirements meetings, held at the contractor facility to discuss the proposed delivered configuration of CM and LM mockups; CSM and LM configuration control panel meetings, conducted by the ASPO to consider proposed engineering changes; Apollo configuration control board meetings, conducted by ASPO to act on changes of known or potential major impact on Apollo missions or changes affecting more than one facet of program design or operations; flight operations plan meetings; crew procedures control board meetings; Apollo EVA task force meetings; and FCST meetings.

The main reviews and exercises, again in approximate chronological order, included conceptual design mockup inspections; an evaluation of the concept of a standing operator for the LM; informal crew station preliminary subsystem design reviews; an in-house study of the Block I CM crew station design by the crewmen and support personnel; a study of LM onboard checkout equipment requirements, which concluded that dedicated equipment of this type was not required; a study of the interactions of mission and subsystem constraints on the design of lunar-surface-stay activities, which established a 35-hour lunar-stay model; Block II CM and LM displays and controls working group reviews; a Block I CM crew compartment lighting review; an MSC study of potential common-use hardware, which excluded most crew station hardware from common use on both the CM and LM vehicles because of conflicts in environmental requirements and schedules; zero-g and lunar-g flight tests in the KC-135 aircraft for evaluation of crew mobility in the LM cabin; final design reviews of crew station hardware (e.g., floodlights and attitude indicators) at vendor facilities; an LM crew mobility review held before the LM critical design review; CM and LM critical design reviews to certify the acceptability of the vehicle design for release for fabrication; postflight analysis of in-flight photography and data from unmanned R&D flights; postfire Block II CM and LM design redefinition reviews; CSM preliminary design concept reviews (preliminary design reviews) held to review proposed redesigns in the areas of basic configuration of internal stowage provisions, ECS modifications, crew-operated mechanisms related to the unitized couch, the unified hatch, and various secondary items affecting crew operations; customer acceptance readiness reviews to formally review the manufacturing accomplishments for each vehicle, to evaluate systems performance as obtained during checkout operations, and to verify that all mission constraints were valid and that the module was capable of stated performance and ready for delivery; an LM lighting/reflection review conducted in the LM mission simulator at MSC to examine potential window reflection problems resulting from approved fireproofing changes; CM foldable-crew-couch reviews; evaluations of CM EVA hardware and procedures in the KC-135 aircraft and in the water immersion facility (WIF); vehicle weight reduction reviews; evaluations of LM crew station procedures and lunar-surface tasks in the KC-135; and CSM and LM thermal-vacuum tests in the Space Environmental Simulation Laboratory at MSC.

Crewmen assigned to specific missions also participated in a multitude of operational, mission-peculiar reviews and exercises not previously listed. These reviews included bench checks of CM and LM crew equipment, altitude chamber tests for their specific vehicles, and specialized equipment exercises. The Apollo 11 prime crew participated in approximately 40 of these mission-peculiar reviews.

A Unique Organizational Approach

The magnitude and complexity of the Apollo crew station design and development task required new approaches in organizational methodology. In response to this challenge, several organizational structures and entities were established at MSC that were rather unique to aerospace crew compartment development programs. These organizational tools contributed significantly to the success of the Apollo crew station development effort.

Three engineering organizations at MSC shared the responsibilities of crew station development. An engineering and development (E&D) organization had the primary responsibility for hardware development and integration, including implementation of requirements, manufacturing, test, and checkout. A separate flightcrew integration organization had the primary responsibility for flightcrew/vehicle interface and integration. A third organization served as a focal point in the ASPO for the analysis and resolution of crew integration requirements and problems. These MSC organizations worked closely with their contractor counterparts, often on a day-to-day basis, in the resolution of crew station development problems.

The flightcrew integration organization coordinated the design, development, and operational aspects of the Apollo crew station and of the crew-related interfaces and served as the focal point for the coordination of all crew requirements and inputs into flight hardware development and checkout. Crew station subsystem managers in this organization were assigned the primary responsibility of coordinating the developmental and operational capabilities of the spacecraft as related to crew interfaces. The function of the crew station subsystem managers complemented the hardware-responsibility function of the hardware subsystem managers of the E&D organization. The FCST was also structured within the flightcrew integration group at MSC. The key responsibilities of the flightcrew integration organization included the following.

1. Establishment of crew-related functional design criteria for spacecraft crew stations, including lighting, displays and controls, stowage, and crew access and accommodations

2. Support and management of crew station and crew-related interfaces during design, development, and implementation

3. Development of requirements for and procurement, fabrication, and maintenance of mockups, trainers, and other supportive equipment for flightcrew training and evaluation of crew station equipment

4. Design, development, procurement, fabrication, and management of crew operational equipment (e.g., cameras) in support of operational and experimental objectives for manned Apollo missions

5. Provision of equipment and support for developmental and operational procedures and tests in zero-g aircraft; also, operation of WIF's to develop equipment and procedures and to provide training for crews when simulated variable-g levels were necessary for extended time periods

6. Provision of support teams to coordinate the availability of all stowed equipment to support flight hardware tests and launch schedules, to participate in the stowage of spacecraft for tests and for launch, to assist during test and checkout flows at major spacecraft reviews, and to serve as the focal point for contact with the crew before lift-off

7. Development, management, and scheduling of systems training for flightcrews, flight controllers, and other Government and contractor personnel

The involvement of MSC astronauts in all facets of Apollo crew station design and operations contributed greatly to the success of the Apollo Program. Astronauts were involved in early Apollo Program decisions, such as the change from the EOR to the LOR mode for lunar missions, and they participated in most of the simulations, meetings, reviews, exercises, and tests previously discussed in this report. In addition, astronauts served or were represented on all high-level change and review boards and on most lower level boards.

Before assignment to a specific mission, astronauts were assigned individual responsibilities in technical disciplines, ranging from familiarization with Apollo mission operations and software to membership in the KSC altitude chamber board. This arrangement was beneficial in several aspects including improved dissemination of information, presentation of the "pilot's point of view," and of course the preflight educational value to the astronauts themselves. Astronaut participation in crew station design and development did not end with a flightcrew assignment for a particular mission; instead, participation was redirected to aspects pertaining to end-item hardware and the operations to be used in accomplishing their specific mission.

DESIGN AND DEVELOPMENT EXPERIENCE

The information that follows is a chronological synopsis of selected events that occurred during the design and development of the Apollo CM and LM crew compartments. The intent is to give a representative sampling of significant events that illustrate the application of the engineering requirements and methodology discussed in the previous sections of this report. Where similar events occurred for both Apollo vehicles (CM and LM), reference to the experience on both vehicles is generally omitted for the sake of brevity (e.g., the conceptual LM mockup reviews were arbitrarily selected for discussion although conceptual reviews were conducted for both spacecraft).

1962

<u>July 10, 1962.</u> - The first Apollo CM spacecraft mockup inspection was held at the contractor's facility.

<u>September 1962.</u> - A completed wooden mockup of the interior arrangement of the Apollo CM was received at MSC from the CSM contractor. An identical mockup was retained by the contractor for design control. Seven additional CM and SM mockups were planned: a partial adapter interface, a CM for exterior cabin equipment, a complete

SM, two spacecraft for handling and transportation, a crew support system, and a complete CSM. A mockup of the G&N equipment had been completed.

December 21, 1962. - A lunar-landing mission design plan that described crew activities for the Apollo lunar-landing mission was prepared. The plan delineated crew functions, assignments, and tasks for both normal and alternate mission sequences. Crew activities were based on the following basic guidelines.

1. The spacecraft will be designed for manual operation with no requirement for unmanned missions.

2. Primary command will be onboard the spacecraft. The capability will exist to perform the mission independent of ground-based information to increase reliability, accuracy, and performance.

3. The crew will control or direct the control of the spacecraft throughout all mission phases. Status of systems will be displayed for crew assessment and mode selection. The spacecraft will be designed so that a single crewman can return the CM to a preselected Earth landing site.

4. Automatic systems will be used to obtain precision or speed of response or to relieve the crew of tedious tasks. All automatic control modes will have manual backup modes.

5. The initiation and subsequent control of aborts will be primarily the responsibility of the crew. Mission Control Center crew safety responsibility will consist of advising the crew of observed malfunctions and recommending a course of action.

6. An in-flight test system (IFTS) will be used by the crew to implement fault detection and isolation. Spare IFTS components and modules will be provided so that the crew can accomplish onboard maintenance and repair. (This scheme was later abandoned in favor of increased system reliability and redundancy. See discussion of "First Quarter of 1964" later in this section.)

1963

March 5 and 6, 1963. - A spacecraft lighting meeting was conducted at the CSM contractor's facility with the CSM and LM contractors and MSC personnel participating. Requirements for a flashing rendezvous light, external position lights, and exterior vehicle floodlights were discussed. Internal lighting techniques were also discussed. Only a few CM instruments would be integrally lighted, whereas all LM instruments would have (red) integral lighting. The CM would have 10 floodlights equipped with red filters capable of being swiveled; the LM would have separate red and white floodlight systems. The CM panels would be illuminated by floodlighting; the LM would have edgelighting (probably EL).

March 12, 1963. - The LM contractor completed a NASA-requested study on the feasibility of using CM and Gemini hardware for the LM design. For the purpose of this study, common-usage hardware was subdivided into four classifications: complete common usage, modified common usage, potential common usage, and noncommon

usage. The study concluded that the G&N displays were the only equipment that could be classified as completely common usage (i.e., the hardware could be accepted and installed as is, without modifications). Four Gemini meters were classified as modified common usage and the remaining display and control hardware as potentially common or noncommon. The LM contractor noted its findings to be preliminary because much of the possible common-usage equipment had not been completely defined, other equipment had not been specified, and most had not been mechanized.

August 7, 1963.- A 2-month evaluation of the concept of a standing operator for the LM was completed by MSC. The evaluation consisted of engineering studies and the preliminary design of several configurations, including mockup hardware. It was concluded that a standing-operator concept was indeed feasible for the LM and offered several advantages over the more conventional seated-operator concept, including improved external area of view with smaller windows, increased mobility for seat area ingress and egress, and substantial weight saving in seat and window structure. Photographs, sketches, and other data were subsequently forwarded to the LM contractor for use in the design of the LM restraint system.

September 16 to 18, 1963.- The first official LM mockup review was conducted at the contractor's facility. The principal article for inspection and review was the M-1 mockup, which was a full-scale representation of the LM ascent stage crew compartment constructed primarily of wood and cardboard. The compartment was equipped with models of basic equipment, including two crew support and restraint concepts designated as the "cage" (restraint straps built into a metal framework that closely fit the astronaut's shape) and the "barstool" (a metal stool and overhead restraint straps). Two crew-mobility demonstration rigs (plywood representations of the ingress/egress tunnels, hatches, and interior confines of the crew compartment) were used in conjunction with an overhead support arrangement to simulate 1/6-g lunar operations. In addition to the M-1 mockup, five full-scale representations of alternate forward-cabin geometric configurations were displayed.

The objectives of the M-1 mockup review were to establish a procedure for this and subsequent mockup reviews; to review and establish a design freeze on the frontal geometry of the ascent stage; and to inspect, review, and critique crew visibility, general location and placement of display panels, seating and restraint, location and basic type of hand controller, hatch arrangement and space allocation for ingress/egress, ingress/egress procedures, and crew station and cabin equipment arrangement.

A total of 33 requests for action were submitted during the review. The significant results were as follows.

1. Review procedures: The procedures established during the review generally were acceptable.

2. Ascent stage geometry: The frontal geometry of the ascent stage was determined to be acceptable, with minor exceptions (noted later).

3. Crew visibility: The window shape and visibility provided for the design eye position were acceptable. The contractor was requested to study the possibility of improving visibility from the forward eye position. (It was also noted that a study of

the adequacy of the M-1 windows for the MSC proposed ascent guidance technique would be required.)

4. Panel location and placement: Further improvements might be realized in conjunction with the support restraint study. The detailed location of specific display instruments required further improvement.

5. Support and restraint: The concept of a standup position for both LM crewmen was approved. It was believed, however, that the M-1 restraint provisions unduly restricted crew mobility.

6. Location and type of hand controller: Controllers were positioned too low and lacked suitable arm support for fine control. The basic type of hand controller could not be evaluated in this mockup.

7. Hatch arrangement and space allocation for ingress/egress: The provisions were satisfactory except that the use of a special tool for hatch operation was questioned.

8. Ingress/egress procedures: The procedures were considered acceptable. It was shown that reduction of the hatch diameter at the exit end would be undesirable.

9. Crew station arrangement: The arrangement was generally acceptable. Specific details of flight control provisions would require further MSC/contractor study.

10. Cabin equipment arrangement: The arrangement was adequate to the degree represented.

October 28, 1963. - An LM-CM displays and controls commonality meeting was held at MSC to explore areas in which commonality might be achieved and to provide a plan of action. Areas discussed included principles of layout, switch and nomenclature conventions, and common specifications – both functional and environmental. Discussion of certain subsystems resulted in an identification of areas of commonality unique to a subsystem as well as in general guidelines applicable to all display and control items. Items discussed included the following.

1. Switch position and location conventions: General agreement was reached that the principles in aircraft standards and military specifications were applicable.

2. Lighting systems and criteria: The difference in mission environments justified the wide difference in lighting systems between the CM and LM. Signal lights, colors, and extinguishment techniques were agreed upon.

3. Hardware commonality: It was generally agreed that, in the area of similar equipment, the greatest program cost and schedule benefits could be derived from the common vendor approach (as opposed to a common specification approach), thus effecting joint procurement.

4. Preparation of interface control documents: It was agreed that the results of the meeting should precipitate the preparation of interface control documents addressed

to the following areas and equipment: nomenclature, switches, floodlighting, gages, annunciators, caution and warning (C&W) lights, clocks and event timers, hand controllers, and counters.

November 19 and 20, 1963.- The MSC Apollo docking interface panel recommended that the center probe and drogue be considered as the Apollo docking concept and that contractor efforts be directed toward the development of this concept. It was agreed that the center probe and drogue concept could be developed into a workable docking system with a minimum or near-minimum weight penalty, compared to the other six docking systems that had been considered. It was noted that a major contractor effort would be required for the development and demonstration of a satisfactory crew transfer capability.

December 5, 1963.- A special CM electrical power system review was conducted at MSC in which the electrical power system design was critiqued by astronauts and other flightcrew operations personnel. Items discussed included the fuel cell diverter valve design, cryogenic heater operation, IFTS philosophy, the feasibility of recharging the entry and postlanding batteries, and the provision of an emergency lighting capability.

1964

February 13, 1964.- A 4-month study of the Block I CM crew station design was completed. The study, conducted by MSC flightcrew operations personnel (including astronauts), had been set up under the auspices of the ASPO in conjunction with vehicle contractor logistics and design engineering personnel. The salient review comments were as follows.

1. Consideration should be given to mechanizing abort functions into a single removable panel.

2. The SCS control mode select panel should be converted to a function select panel so the crew could more effectively use the GN&C systems capabilities (e.g., individual function switches could permit selection of attitude control modes on a "per axis" basis).

3. The attitude hand controller should be mechanized so that a soft stop would be encountered before actuation of the direct (hardover) switches.

4. The flight director attitude indicator (FDAI) attitude presentation should be improved by alining the navigation and spacecraft axes. The attitude error and rate needles should also be positioned so that their common neutral position is at the center point of the instrument face.

5. Manual operation of the ECS appears to be very difficult because of sensor locations and the display and control mechanization.

6. The sequential events lights and override switches should be grouped together and arranged according to mission modes; i.e., launch escape system abort, high-altitude abort, etc.

7. The Apollo crew station must be designed with the capability of maintaining the crew in space suits, except for short periods required for crew body functions, until the practicality and safety of shirt-sleeve operations are proved by flight tests.

March 19, 1964.- The second formal LM mockup review was conducted at the contractor's facility. The principal article for inspection and review was the TM-1 mockup, which consisted of a full-scale descent stage with landing gear and an ascent stage with a complete interior. The TM-1 mockup reflected improved designs that resulted from the earlier M-1 mockup review.

The objectives of the TM-1 mockup review were as follows.

1. To inspect, review, and critique the location, shape, arrangement, design, and operation of crew/crew-station equipment and interfaces; the location of all antennas and descent-stage scientific equipment bays; the concept of docking drogue installation and storage; and the overall vehicle configuration and arrangement – all for the purpose of establishing a design freeze that would be incorporated into the final mockup (designated M-5)

2. To demonstrate four different means of descending from the outside surface of the ascent stage to the lunar surface and returning, in a pressurized space suit and in a 1/6-g environment.

3. To demonstrate mobility, support/restraint, and access to all items in the cockpit and equipment tunnel while wearing a space suit (both pressurized and unpressurized)

4. To demonstrate cockpit floodlighting as proposed for the LM (EL panel lighting would be demonstrated at a later date)

5. To demonstrate the zero-g foot retention method (shoes with Velcro tape hook soles and floor lines with Velcro pile)

First quarter of 1964.- The Block II design of the CSM was initiated. Whereas the original CSM (Block I) design had been based on the EOR mode in which no LM was used, the Block II CSM would be designed to accommodate the LOR technique, which used an LM. The basic change between the Block I and II designs was the addition of the provision for docking and crew transfer between the CM and the LM. Design improvement and weight reduction changes were also incorporated at this time, and the philosophy of in-flight maintenance was eliminated in favor of higher reliability redundant systems.

The major changes included the following.

1. Addition of a docking tunnel and system for docking and crew transfer between vehicles

2. Addition of an umbilical scheme to temporarily power the LM and for spacecraft/LM adapter panel deployment

3. Addition of interface hardware to permit pressurization of the LM by the CM

4. Internal rearrangement

5. Addition of EVA capability

6. Addition of EL lighting and the entry monitor system (EMS)

7. Addition of the digital autopilot and redundant attitude display

July 22, 1964. - An interdivision meeting was held at MSC to assess in-house LM mockup requirements. As a result of this meeting, a statement of work was released for the fabrication of the first MSC-based LM mockup. The crew integration mockup would be used in crew station geometry studies, crew/equipment integration, preliminary developmental evaluation of scientific and operational equipment placement, and operational problems and crew station familiarization.

The specific advantages of locating a separate mockup at MSC were (1) the immediate availability of the device for performance of its intended functions by engineering, training, and flightcrew personnel without extensive travel costs, and (2) the release of the LM mockup at the contractor's facility from constant reviews, allowing it to be more fully used by the contractor as an engineering development tool.

September 9, 1964. - A working group (CM contractor and MSC) review of the CM Block II controls and displays was conducted as a forerunner to a Block II mockup review scheduled for September 30. Recommendations and results from this meeting included the following.

1. The EMS should be edgelighted rather than illuminated by the floodlights.

2. A standard DSKY size was approved.

3. A manual staging switch was added to panel 19.

4. Flight control switches were grouped and functionally arranged in a prime reach area of the CDR's instrument panel.

September 10, 1964. - The first CM crew integration systems meeting was held at MSC. The agenda items included identification and discussion of "open items," review of the Block II hand controller configuration and status of the MSC hand controller specification, and review of display and control panel arrangement.

September 10, 1964. - The first spacecraft design integration system meeting was held at MSC. Extravehicular crew transfer was a major topic of discussion in regard to the rationale for developing design criteria, access hatch design and capabilities, and crew-transfer-aids design and capabilities.

Third quarter of 1964.- A major effort was put forth during the third quarter of 1964 on the Block II CM redesign, with primary emphasis on the GN&C system and associated controls and displays. Major changes and events included the following.

1. Numerous GN&C system switching functions were moved to the control panel.

2. The inertial measuring unit and the FDAI were realined to correspond to the vehicle body axes.

3. A second FDAI was added.

4. One translational controller was deleted (equivalent redundancy would be built into the remaining controller).

5. The MSC attitude controller functional specification for the CM and LM was finalized.

6. The EMS configuration was established.

7. A Block I CM crew compartment lighting review was conducted in a mockup at the CM contractor's facility. The concept was considered adequate for Block I, with a few changes.

8. The unitized couch concept was discussed at MSC. The main advantages were reductions in weight and volume.

9. The CM crew restraint system and lateral hatch mockup were evaluated and found acceptable with minor changes (shoulder harness needed stiffer webbing).

Major changes and events relative to the LM included the following.

1. An EL lighting review was conducted in the TM-1 mockup. The concept was found to be acceptable.

2. An extensive review of the timing requirements for the Apollo mission was conducted by MSC.

3. An MSC study identified an operational requirement for continuous monitoring of descent propellant quantity, as opposed to the current configuration of a low-level discrete.

4. An overhead window was implemented for the LM CDR, and the forward docking tunnel was deleted.

5. The basic ground rules for man's role in the LM were restated for the benefit of the G&N redefinition program.

a. Man should be an integral part of the loop, not a passive monitor.

b. Vehicle control should be fully automatic or fully manual for higher performance and safety: automatic for high-accuracy, rapid-response, repetitious, and predictable tasks; manual for nonroutine maneuvers, flexibility, judgment, complex logic, and transition between modes.

October 5 to 8, 1964.- The third official LM mockup review was conducted at the contractor's facility. The principal article for inspection and review was the M-5 mockup, a full-scale metal mockup (previous mockups were wood) that represented complete interior and exterior arrangements. The M-5 was the last in the series of mockups fabricated by the vehicle contractor for the purpose of establishing the LM configuration. Additional items presented for review were "hard" mockups of equipment, engines, the RCS, antennas, system and subsystem components, and structure and line runs. Demonstrations were also included of the external mobility techniques of descending to and ascending from the lunar surface and of the internal mobility tasks in the cockpit while wearing a space suit, both pressurized and unpressurized.

The principal objectives of the M-5 inspection and review were to definitize the LM configuration for continued development and qualification and to establish the configuration as the basis for tooling and fabrication of initial LM end-items.

A total of 148 requests for action was submitted during the review. The significant results were as follows.

1. Crew provisions: Crew provisions were acceptable in concept in almost all cases and in the method of implementation in a majority of cases. Discrepancies included the following items.

a. Shoe height adjustment was found unnecessary.

b. Armrests were too restrictive and cumbersome.

c. The controller/armrest geometry was undesirable.

d. The PLSS donning and recharge stations required further refinement.

e. Lithium hydroxide (LiOH) stowage containers required rework.

f. Stowage provisions did not exist for the flight data file.

g. Lunar egress equipment (tunnel, handgrips and handles, and ladder) required refinement.

2. Displays and controls: Displays and controls were generally acceptable. Discrepancies included the following items.

a. The thrust-to-weight indicator needed relocating to permit viewing from both stations.

b. Certain panel nomenclature was found to be inconsistent with accepted CM panel nomenclature (e.g., left and right instead of ±yaw).

c. The X- and Y-mark buttons required relocating from the DSKY to the AOT for adequate access.

3. Lighting: The lighting was judged to range from generally good to excellent with the exception of the dome/lunar excursion light. The dual function of a single light was rejected; separate units would be provided instead.

November 13, 1964. - The existing DSKY design for the Block II CSM and for the LM was found to be incompatible with the existing display panel design of both vehicles from the standpoint of lighting, nomenclature presentation, and caution/warning philosophy. To ensure compatibility and consistency with existing spacecraft display panel design, MSC established the following mandatory operational requirements for design of the DSKY.

1. All caution lights on the DSKY were to be gated into the primary guidance and navigation system (PGNS) caution light on the main instrument panels of both vehicles and into the PGNS caution light on the LEB panel of the CM. Furthermore, any caution signal gated into the master PGNS caution light should appear as an individual caution light on the DSKY. Warning lights would not be displayed on the DSKY, but warning signals would be gated into the appropriate fail lights located on the main instrument panels and in the LEB.

2. Definitions, method of display, design philosophies, nomenclature, and lighting were to be functionally compatible with both the CM and LM and were to conform to pending interface control documents.

1965

January 1965. - An LM spacecraft/crew interface reduced-gravity test plan was prepared by the LM contractor. The following revisions were recommended by MSC.

1. Flight control studies should not be conducted because Mercury experience has shown that such tests of limited duration prove inconclusive.

2. Test subjects should be NASA and LM contractor personnel and should be supported by NASA medical and suit technicians.

3. All equipment being evaluated or being used in conjunction with a particular test shall be spacecraft prototype or production hardware directly applicable to the LM program.

4. Reduced-gravity tests should not be used to establish design criteria but to verify design of prototype hardware.

It was decided that numerous controls and displays identified as common-usage hardware should be declassified as such and that the vehicle contractors should instead pursue independent procurements. The two major stumbling blocks to common usage were environmental requirements and schedules. Environmental requirements differed between the two vehicles. The requirements were more severe for the LM but did not cover the entire test range for the CM. To provide a common environment with respect to vibration, it would be necessary for MSC to establish this common spectrum and impose it upon the major contractors where applicable. This action would result in a slip in hardware delivery schedules.

February 1965. - It was concluded at MSC that an identical display technique should be used for fuel and oxidizer quantities in both the LM and the CM. It was also recommended that all propulsion quantities be displayed in percent of quantity remaining. It was believed that standardization in this area would significantly enhance inflight propellant monitoring techniques.

May 10, 1965. - An alternate approach to the standard "two out of three" failure logic was established for Apollo telemetry measurements. Where critical operational decisions must be based on noncorrelatable parameters, dual (not triple) redundant sensing and telemetry measurements would be provided. The rationale for two sensors (not three) is as follows.

1. If both sensors read within (or beyond) operating limits, the measurements are considered to be valid and the parameter status is considered to be satisfactory (or unsatisfactory).

2. If one sensor reads within limits and the other indicates a failure, the satisfactory measurement is considered to be valid and the indicated failure is considered to be invalid. (For the failure indication to be valid, not only must the system have failed but a sensor must correspondingly fail to show a satisfactory reading. This occurrence is considered to be of far lower probability than a single instrumentation failure.)

June/July 1965. - Zero- and lunar-gravity flight tests were conducted in a KC-135 aircraft to evaluate crew mobility in the cockpit/cabin configuration of the LM vehicle. All tasks were performed without the use of a restraint system. Handgrips and the adhesion between Velcro shoes and the Velcro-covered cabin floor were the sole means of restraint during the weightless state. These tests (1) certified the accessibility of LM controls, (2) identified the maximum acceptable operating torque for ECS valves, (3) demonstrated that an environment of weightlessness or lunar gravity may enhance rather than deter several of the tasks required during a lunar mission, (4) demonstrated the need for additional handholds to assist in manipulation of the overhead hatch and other operations, (5) identified the need to redesign the LiOH canister knob handle to accommodate manipulation with a "gloved" hand, and (6) illustrated the need for improved restraint of the crew and crew station equipment.

July 5 to 9, 1965. - The fourth in a series of LM crew integration meetings was held at the LM contractor's facility. The objectives of the meeting were to review and provide an up-to-date summary of the design and development of the LM crew station that had occurred since the M-5 mockup review. Items covered in this meeting included the restraint system, flight kit, helmet and window filters, scientific and crew equipment stowage, lighting, optical aids, and controls and displays.

The salient conclusions and results were as follows.

1. LM restraint system: The current design concept of the support and restraint system was judged acceptable on the basis of the results of ongoing development tests. (Absolute confirmation would be obtained by manned drop tests with LM test article 3 (LTA-3)).

2. Scientific and crew equipment stowage: Action items were assigned to resolve operational requirements and stowage for sequence cameras, in-flight tools, EVA visors, sample return containers, television camera cabling (for operation through the overhead hatch), and the external portable light.

3. Landing and docking aids: The MSC proposed that a collimated reticle device be added to the overhead window to aid docking operations.

4. Controls and displays: The MSC evidenced some concern for the readability of a 60-hour clockface proposed for the LM and the possibility of error in performing the synchronizing operations during the mission. The desirability of changing the range of the digital event timer from 99 minutes 59 seconds to 59 minutes 59 seconds was also discussed. The MSC accepted an action item to investigate the need for the LGC uplink switch and light. The LM contractor indicated that descent propellant quantity gaging was being incorporated.

September 1965. - A 2-year program of LM approach-and-landing simulations by MSC was completed. The study was conducted to develop GN&C hardware and pilot techniques to support a lunar landing. These simulations (1) validated the LM touchdown velocity criteria for the LM to be within pilot control capabilities, (2) demonstrated a strong pilot preference for manual descent engine cutoff, (3) invalidated the use of a digital FDAI because of a lack of trend information, (4) identified a requirement to relocate the descent engine stop switch for improved access, (5) demonstrated the inadequacy of using the CM Block I attitude hand controller within the LM (low-force gradients caused cross-coupling between axes), and (6) demonstrated the effect of pressure suit operations on pilotage techniques and display and control design.

Third quarter of 1965. - Interface control documents that addressed both physical and functional interfaces that existed between the main hardware suppliers were among the numerous crew station documents that were completed and signed off. The "CM-LM Transferable Equipment" interface control document, for example, established specific technical requirements for each item of equipment to be transferred between the CM and the LM; defined the transfer requirements; and referenced the documents that controlled the size, shape, weight, stowage locations, and mounting provisions for items of transferable equipment. Interface control documents were also generated for displays; controls; nomenclature, markings, and color; and lighting.

October 14, 1965.- Stowage of equipment in the Apollo spacecraft and the need for mockups were reexamined at MSC. It was noted that, under present plans, 2 full years would elapse between the last Block I mockup update and review and the flight of spacecraft (SC) 012. Since that mockup review, there had been numerous design changes to the crew compartment, which had not been physically inspected for the effect or suitability of the change. In addition, little operational gear and no scientific equipment had been integrated into the spacecraft. To remedy this situation, the following recommendations were made.

1. The vehicle contractors and MSC should maintain mockups that represent the precise interior configuration of the spacecraft and in which all necessary stowage exercises can be performed and demonstrated.

2. A series of activities should be instituted in which the contractors develop the integrated stowage; MSC then inspects and approves, and, following approval, the contractor's mockup undergoes change control to the next succeeding spacecraft.

3. The MSC mockups should be maintained in the configuration approved at the time of the review of the contractor's mockup. As other problems develop during training on this unit, or during further studies of the activity for the mission, the approved configuration should be a suitable baseline for making adjustments to the spacecraft as required.

1966

January 7 and 10, 1966.- An LM crew mobility review was conducted in the LM mockup at MSC. The purpose of the review was to evaluate crew tasks and equipment before the forthcoming LM critical design review. Four astronauts and three contractor employees served as test subjects. Thirty-eight review item dispositions (RID's) were generated, which resulted in a variety of action items such as

1. Evaluation of transfer procedures under weightless conditions in a KC-135 aircraft

2. Further examination of the use of television through the top hatch

3. Provision for external handholds near the front hatch to aid in egress/ingress

4. Provision for certain equipment with additional protection against possible contact and damage

First quarter of 1966.- A three-phase critical design review was conducted for LTA-8 (the thermal-vacuum test vehicle), LM-1 (originally planned as the first manned vehicle), and LM-4 (originally planned as the first lunar-landing vehicle). The primary objective of the review was contractor/MSC agreement on the acceptability of the design for fabrication.

The first phase of the review was conducted at MSC, and the second phase was conducted at the contractor's facility. The prime requisite for the first two phases was

satisfaction of the technical requirements established by the LM master end-item specification as they applied to the LM-4 vehicle. The third phase, also conducted at the contractor's facility, was dedicated to the acceptability of the vehicle in regard to vehicle and mission operations.

The following is a summary of actions that affected LM crew station design and operations.

1. Crew compartment design: Eight requests for changes (RFC) were approved that required hardware changes such as the addition of ceiling covers to protect wiring and prevent debris from collecting in this area and the addition of more Velcro to aid in equipment handling and stowage.

2. Crew station operations: Eleven RFC's were approved. All required various studies, and most resulted in procedures or hardware modifications. One study changed the method and hardware for the deployment of the very-high-frequency (vhf) EVA antenna (manual assembly by an astronaut standing in the top hatch was changed to semiautomatic erection by actuation of a crew compartment control). Another study produced methods for in-flight checkout of the entire C&W system.

3. Displays and controls: Twenty RFC's were approved, 10 of which required hardware changes (e.g., a PGNS minimum-impulse mode was added for fine attitude maneuvers). The remaining 10 RFC's required various studies, some of which resulted in hardware modifications (e.g., one study identified the need to provide individual heater controls for RCS thruster quads).

4. Lighting: Two RFC's were approved and required hardware changes. Individual continuous dimming of the forward floodlights would be implemented, and the location, color, and intensity of the lunar contact light would be improved. A study was also commissioned to examine the need for window shades to aid in crew station temperature control.

May 18, 1966.- The CSM SC-014 critical design review was conducted at the contractor's facility. Spacecraft 014 was planned to be the second manned Block I spacecraft. Approximately 50 RID's were dispositioned, 30 of which required hardware changes. The remaining RID's were primarily addressed to discrepancies with GFE and therefore did not require action by the vehicle contractor. Most of the RID's were made retroactive to SC-012, the first manned CM.

The following is a sampling of RID's that were approved for implementation.

1. Improve design, construction, and fit of the weightless restraint crewman sandals.

2. Protect wiring bundles from traffic.

3. Redesign cam lock fasteners on the right-hand auxiliary food box for proper functioning.

4. Rotate penlights in stowage compartment to permit detection of inadvertently actuated lights.

5. Provide more Velcro stowage and restraining areas on aft bulkhead.

6. Provide a spare COAS light bulb.

7. Color-code crew/day food packages (nine man-meals) and incorporate a lanyarding scheme such that 1 day's supply of food (for three crewmen) may be identified and removed from the stowage containers each day.

November 1966.- Procedures for maintaining stowage lists were established. The first official stowage list was to be issued by the CM vehicle contractor and submitted for NASA approval. Subsequent revisions to this list (for each spacecraft) were to be forwarded to the vehicle contractor from NASA according to the following schedule.

1. Three weeks before stowage review

2. One month before the CCFF test

3. One week before the manned altitude chamber run at KSC

4. Before the flight for documentation of launch configuration

5. As necessary to incorporate significant changes

Block II stowage lists issued by the NASA FCST's would consist of five parts: a CM launch stowage list, an LM launch stowage list, a CM-LM transfer list, an LM-CM transfer list, and a CM entry list.

1967

February/March 1967.- As a result of the SC-012 fire, a series of CSM Block II and LM design redefinition reviews was conducted at MSC. Approximately 100 design and procedural changes were proposed for each vehicle. Most of the proposed changes were subsequently implemented.

Changes proposed for the CSM included redesigning plumbing lines and shields, implementing a rapid repressurization sceneme, relocating the ECS controls, using air for pad operations, providing a "folddown" mechanism for the rotational controllers, adding a CSM tracking light, implementing nonmetallic materials criteria, implementing a unified hatch, providing an emergency oxygen mask, and implementing design improvements for the existing crew couch and developing a foldable couch for later vehicles.

Changes proposed for the LM included providing power-down capability for all connectors mated/demated during flight operations, deleting single-point failures within vehicle subsystems, providing a method for verification/adjustment of the LM COAS/CM

docking target alinement, providing integral restraints (instead of special connections) for oxygen hoses, providing a crew station fire-extinguishing device for the pad and for in-flight use, providing protection for the remaining crewman in the event of catastrophic damage to the suit of one crewman, providing the capability for continuous S-band communications during all lunar operations within the line of sight of the Earth independent of pilot maneuvers, providing switch isolation of each attitude and thrust/translation hand controller, and providing scale sensitivity selection for the FDAI rate needles.

Second quarter of 1967.- As a result of the reviews held after the SC-012 fire, numerous design and procedural changes were instituted. Changes instituted for the CM crew station are summarized as follows.

1. Cabin materials: An improved materials selection and substitution program was established. The major bulk combustibles in the cabin were removed, and substitutes were evaluated.

2. Space-suit materials: State-of-the-art nonflammable fabrics, having 10 times the fire resistance of former materials, were incorporated into an integral cover layer for the space suit.

3. Side hatch: A unified, outward-opening, quick-release side hatch replaced the separate pressure and heat shield hatch. Essential features of the new hatch were manual release for normal or high internal pressures, operation either internally or externally, and manual operation for protection against inadvertent opening.

4. Cabin atmosphere: The option would be provided to use either air or 100 percent oxygen for ground tests, prelaunch and launch. The final atmosphere would be determined from ongoing boilerplate fire-safety tests.

5. Equipment protection: Protective covers were added to exposed oxygen and glycol plumbing lines and electrical wiring.

6. Fire protection: An emergency breathing mask system was provided to permit crew operations if a cabin fire occurred during shirt-sleeve operations. An additional pressure relief valve and a second oxygen surge tank were added to permit rapid depressurization and repressurization, respectively.

7. Fire extinguishment: A portable, crew-operated fire extinguisher, which consisted of a special hose and nozzle connected to the spacecraft water supply, was developed.

The following additional changes were also approved for incorporation into the CSM design.

1. Certain ECS controls were relocated to facilitate emergency operations.

2. A manual lockout was provided for the postlanding vent valve to preclude accidental decompression.

3. An automatic battery bus tie upon abort initiation was implemented to reduce crew load at this time.

4. The hand-controller 1.7-second timer was replaced with a 3-second timer for subsequent operations with the LM.

5. Minor changes were made for improved crew couch operations, and the couch J-box was relocated to prevent wiring damage.

6. Redundant power was provided to the S-band system, and 17 new measurements were added to the operational instrumentation system.

July 13 to 18, 1967. - Joint CM contractor/NASA discussions were held at the contractor's facility on the proposed delivered configuration of CM mockups MSC 1 and 2 and the KSC egress trainer (KSC-E) as well as the maintained configuration of mockup 28 at the contractor's facility. The purpose of the meeting was to discuss mockup configuration requirements and to agree on the configuration details and the level of fidelity in the following major areas: electrical equipment, GFE provisions, side access hatches, docking tunnels, main display and control panels, oxygen umbilicals, and EVA provisions. It was established that the mockups would correspond to the following initial spacecraft configurations:

1. MSC-1: SC-101 configuration (subsequently SC-104, SC-106, etc.)

2. MSC-2: SC-103 configuration (subsequently SC-105, SC-107, etc.)

3. KSC-E: SC-101 configuration

4. Mockup 28: SC-104 configuration (subsequently SC-105, SC-106, etc.)

Mockup 28 would continue to be used for conceptual design studies and preliminary design reviews until it was scheduled for the SC-104 configuration update.

August 26, 1967. - The top management at MSC conducted a review of CM stowed equipment and stowage provisions. The status, configuration, and composition of both contractor-furnished equipment (CFE) and GFE were reviewed. The following materials and test criteria were established.

1. Materials that burn will be replaced with nonflammable material.

2. Where materials cannot be changed or reliability would be degraded by the change, flammable materials may be used in the spacecraft.

In such instances, they will not be located near ignition sources and will be placed in Beta-cloth bags or metal containers. New materials will continue to be evaluated and will be phased into the program if found to be acceptable.

3. Off-limits material flammability tests will be accomplished to determine the acceptability of materials.

4. Qualification tests will be done using ignition sources that would actually exist in the spacecraft.

5. The high-fidelity CSM mockup would be used for demonstration tests using ignition sources that exist in the spacecraft. Certain items would be added to the low-fidelity boilerplate to acquire earlier data on the acceptability of material changes.

August 1967. - At the request of MSC, the CM and LM contractors prepared documents for their respective vehicles that standardized all crew station displays and controls nomenclature. The primary purpose of these nomenclature listings was to eliminate confusion by technicians, test engineers, or flightcrews when performing acceptance, checkout, or operational flight procedures. Nomenclature within the standard listings conformed to general rules established by MSC (e.g., "When a switch does not have a unique title, the shared title and the upper switch position shall be used to identify the switch.").

September 11, 1967. - A review of the displays and controls configuration and of outstanding problems for the CM thermal-vacuum test vehicle (2TV-1) and SC-101 was conducted at the contractor's facility. Subjects discussed included nomenclature errors; nonfunctional controls; guards for the CMC/gyro display coupler (GDC), RCS purge, and sequential events switches; EVA assist bars and panel protective grills; C&W limits and changes; power interface of the launch vehicle tank pressure/engine gimbal position meters; certain crew station color/marking discrepancies; and dimming requirements for the docking target. The numerous errors and inconsistencies in panel nomenclature and markings identified at the review resulted from an MSC cross-check of display and control layout drawings, individual panel drawings, and EL specification control drawings.

September 1967. - A prototype combined protective grid and ingress handrail for the center portion of the CM MDC was evaluated by astronauts and flightcrew engineers on KC-135 zero-g flights. It was concluded that a protective grid would only be required for Apollo flights involving planned EVA with CM ingress. It was also concluded that the final protective grid should be (1) attachable in flight, (2) stowable in the LM or CM until needed, and (3) jettisonable from the CM after the last CM ingress is performed. It was recommended that redesigned guards should be further evaluated in the new WIF tank at MSC.

October 10 to 12, 1967. - A delta critical design review of the first manned Block II CM (SC-101) was conducted. Measurement change requests and associated documentation were reviewed by contractor/NASA teams to ensure design compliance with NASA contractual directives resulting from postfire redesign efforts. Actions assigned to 30 RID's affecting crew station design and operations included the following.

1. NASA will provide the foot restraint requirements.

2. The contractor will provide revised SC-101 stowage drawings.

3. The contractor will provide data on the unified hatch design.

4. The contractor will submit a nonmetallic-materials control and verification plan.

October 13, 1967. - The first Apollo configuration control board meeting was conducted by MSC. Ground rules for approving changes and conducting subsequent meetings were established. Several material deviations were approved, including the use of existing space-suit oxygen umbilicals made of silicon rubber because the substitution of other materials was not feasible. A review of all CM and LM stowed equipment was conducted. It was decided that the vehicle contractors would be directed to prepare crew station Velcro control drawings that would illustrate all pile and hook Velcro locations within the spacecraft. The total quantity and weight of the Velcro would be limited. A change to disable the PGNS caution light within both vehicles was also approved. (During crew training, flightcrews were annoyed with constant insignificant activations of the PGNS light, which in turn triggered the master alarm light and alarm tone with each activation.)

December 18 and 19, 1967. - The second in a series of Apollo foldable crew couch reviews was conducted; 13 RID's were generated. Five action items accepted by NASA included (1) providing direction to meet the requirement for retention of the crew couch suit pan in the 170° position (to aid in tunnel/G&N station operations) and (2) defining the length of the crew couch calf pan required to maintain suitable back-thigh angles (existing 33-centimeter (13 inch)/10-percentile length would not accommodate smaller and larger astronauts). In conjunction with the foldable-couch review, several items stemming from earlier exercises were evaluated with the following results.

1. A 7.6-centimeter (3 inch) handle extension was judged to be required for access to the cabin pressure dump valves.

2. The relocated position of the spacecraft cabin gas analyzer was judged to be acceptable.

3. Access to the cabin repressurization control was judged to be acceptable.

4. The new L-shaped PGA stowage bag was assessed and approved.

December 1967. - In response to an RID submitted at the phase I customer acceptance readiness review (CARR) for CM SC-101, a set of display and control panel closeout photographs was submitted by the contractor to NASA for review. Numerous nomenclature discrepancies were found and identified to the vehicle contractor for corrective action. Discrepancies included the following:

1. The vhf antenna knob covered adjacent nomenclature.

2. The COAS power receptacle nomenclature was missing.

3. Certain nomenclature brackets were missing.

4. Nomenclature for the postlanding ventilation control was missing.

February 9, 1968. - A nonmetallic-materials requirements document was released by MSC. The purpose of this document was to establish nonmetallic materials selection and acceptance guidelines and to test requirements for control of flammability and toxicity of nonmetallic materials used in the Apollo spacecraft and in applicable test equipment used internal to the Apollo spacecraft during closed-hatch testing. Guidelines concerning control and verification of material and assembly flammability and toxicity were based on the following requirements.

1. Reduction in the probability of ignition

2. Restriction of any fire to a definable area

3. Limitation of the rate and magnitude of the rise of temperature and pressure from any fire to prevent the loss of structural integrity

4. Protection of the crew from the flammability and toxicity effects caused by any fire

5. Implementation of design features concerned with controlling flame propagation and the effects of any fire

Materials were classified and treated as seven different categories.

1. Category A – Major exposed materials

2. Category B – Special applications and minor exposed materials

3. Category C – Crew oxygen supply materials

4. Category E – Material applications in sealed containers

5. Category F – Materials in vented containers

6. Category G – Materials applications in nonflight equipment

7. Category H – Materials in uninhabited portions of the spacecraft

March 1, 1968. - A spacecraft/crew integration plan for manned Block II Apollo CSM and LM missions was released at MSC. As with the previously released Block I CSM plan, this plan defined the specific participation by the primary and backup flightcrews and the FCST in the Apollo spacecraft reviews, spacecraft checkout testing, and prelaunch operations. One significant revision made to the later plan was the addition of a second CCFF test for the CM. The second CCFF test was to be held at KSC and would verify unsuited-crewman emergency egress procedures in a pressurized and unpressurized cabin, accessibility, proper mechanical and electrical functions, operational suitability of all stowed and installed crew equipment for in-flight use, and reentry locations (with the crewmen suited and unsuited).

March 18 to 20, 1968. - Phases I and II of the LM-4 CARR were conducted. A photographic review of the crew station configuration resulted in the identification of numerous panel nomenclature discrepancies. Several panel hardware discrepancies were also detected during an "in the vehicle" review. A request for action was also submitted that recommended providing an extra circuit breaker to prevent a single-point failure that would disable all LM crew station floodlighting. The vehicle contractor subsequently corrected the discrepancies identified.

March 22, 1968. - A mockup utilization plan was released at MSC that established the preparation of mockup utilization request forms and annual milestone projection forms by organizations planning exercises in MSC CM and LM mockups. These forms were to be used to maintain a master schedule for all mockups. In the event of conflicting mockup utilization requirements, availability would be based on the following priorities:

1. Mission-critical requirements
2. Crew training
3. Procedures development
4. Hardware development and evaluation
5. Mainline Apollo but non-mission-related studies
6. Future programs

The plan controlled the use of all 14 vehicle mockups maintained by MSC, which included the one-g static mockups (2 CM, 2 LM), the KC-135 zero-g mockups (1 CM, 2 LM), the KSC-E CM mockup, the neutral-buoyancy mockups (1 CM, 1 LM), the CM-LM EVA trail mockup, the CM-LM tunnel mockup, the KC-135/neutral-buoyancy LM ingress/egress mockup, and the simulated lunar surface LM mockup.

March 25 and 28, 1968. - Protective handrails for the CM MDC were evaluated in the MSC WIF. Procedures and equipment for oxygen purge system (OPS) ingress, PLSS/OPS ingress/egress, and hatch closing were also evaluated. As a result, it was recommended that the handrail configuration used in this test be implemented for the CM.

March 1968. - A review was made of all LM equipment and systems with the intent of reducing inert weight. Most of the changes proposed for the crew station were not implemented because of their effect on mission success and crew safety. Proposed changes included deletion of the television camera system, deletion of the orbital rate drive, earth and lunar (ORDEAL), deletion of one of the two FDAI's, elimination of one or both utility lights, and modifications to the crew station cable run (approved).

A crew procedures control plan was established at MSC. The plan specified methods that were to be used to control flightcrew procedures delineated within the Apollo flight plans and procedures documents, including systems procedures within the AOH; flight procedures documents; and EVA, lunar surface, and photographic procedures documents. The definition and characteristics of two types of crew procedures

were included in the plan. System procedures were defined as the sequence of crew actions necessary to operate a spacecraft system. Flight procedures were defined as the time history of crew actions necessary to achieve a mission objective.

April 22 to 26, 1968. - The LM-3 (first manned LM) crew station procedures and LM lunar surface tasks were exercised on KC-135 reduced-gravity flights. Crew equipment and procedural comments included the following.

1. A more positive method of securing the helmet stowage bags to the ascent engine cover may be required.

2. Donning/doffing of the PLSS could best be accomplished without any restraints attached to the crewman being outfitted.

3. The descent-stage equipment deployment mechanism should be redesigned. Replacement of the deployment handle with a D-ring hooked to a cable-type actuator was suggested.

April 1968. - Photographic documentation requirements were revised for the CM and LM spacecraft. Whereas the earlier plan required the contractors to "photograph the standard configuration of one typical spacecraft through all stages of manufacturing," the revised plan required that all vehicles be photographed. Spacecraft managers and assigned flightcrews were to be furnished a complete set of display and control panel photographs, and project engineering would be supplied with a set of crew equipment photographs.

May 21, 1968. - The CSM contractor generated a plan to resolve a recurring problem of discrepancies in crew station display and control and ECS placarded nomenclature. Highlights of the plan were an engineering review of all applicable drawings, a manufacturing review of drawings and panels, quality control checks before panel assembly, and establishment of change verification record books for use in the installation area to document all open work to be performed on display and control panels and black boxes.

May 22, 1968. - The MSC directed the CM vehicle contractor to terminate the preparation of standard aircraft-type crew checklists for each vehicle. Instead, the checklists would be prepared and maintained by MSC personnel and reviewed by the contractor. This was believed to be a more effective approach toward integrating the checklist with other mission-related documents being maintained at MSC.

June 1968. - The CM (vehicle 2TV-1) thermal-vacuum test was conducted at MSC. The flightcrew and FCST made numerous recommendations in those areas where it was considered that a technical or procedural change would result in safer or more effective future thermal-vacuum testing and/or vehicle flight. Recommendations germane to crew station design and operations were implemented and included the following.

1. Investigate the possibility of changing the design or location of the cabin mirror assemblies to provide greater visual coverage.

2. Change the location of the television camera to reduce interference with crew activity and provide a satisfactory clamping device.

3. Resolve the deficiencies reported with stowage volumes (stuck doors, interference, and distortion).

4. Investigate the possibility of providing in-flight pens that would write satisfactorily on Nomex paper.

5. Assure proper fit of window shades on each vehicle.

6. Add screwdrivers (flat and cross-point), small pliers, spare B-nut wrench, and small crescent wrench to the toolkit for use in making onboard repairs and adjustments.

7. Provide onboard procedures for use of emergency oxygen masks.

September 5, 1968.- Flightcrew support teams were assigned to provide support for the first five Apollo missions, which would use the following vehicles, respectively: CSM-101, CSM-103, CSM-104/LM-3, CSM-106/LM-4, and CSM-107/LM-5. The FCST's were to provide the flightcrew support functions enumerated in the spacecraft/crew integration plan for manned Block II Apollo CSM and LM missions and were to supplement the role of the crew station subsystem managers on their assigned spacecraft. As defined in the integration plan, each FCST consisted of a team leader, crew station engineers, crew equipment engineers, spacecraft systems engineers, and a training coordinator.

October 11 to 22, 1968.- The first manned Apollo flight was accomplished. This mission qualified the CSM for operation in the Earth-orbital environment and demonstrated its readiness for flight tests in the cislunar and lunar-orbital environments. The Apollo 7 flightcrew found that the CM crew station was adequately configured for the mission and presented no compromise to performance of their required duties. Six crew station anomalies were experienced – four display and control items, one lighting anomaly, and a window contamination problem.

December 21 to 27, 1968.- The second manned Apollo flight was conducted. Apollo 8, the first manned lunar orbit mission, qualified the CSM systems for manned lunar flight. Relatively few problems were encountered in regard to crew station design and operations. Equipment stowage, displays and controls, and lighting were found to be adequate. Three crew station anomalies were experienced – EMS abnormal indications, excessive noise emissions from cabin fans, and window contamination.

1969

January 21, 1969.- The first Apollo 11 FCST meeting was held at KSC. Action items resulting from the meeting included the following.

1. Investigate the fidelity of the LM descent-stage training equipment.

2. Investigate PLSS checkout requirements in the altitude chamber.

3. Schedule probe/drogue and vehicle emergency egress training exercises.

4. Prepare for an upcoming LM and CM crew equipment bench check.

February 6 and 7, 1969.- The first lunar landing mission/Apollo 11 prime and backup crews participated in a bench review of flightcrew equipment at KSC. Deficiencies/discrepancies that were noted included the following items.

1. CSM-107:

a. Crew equipment shortages included 23 GFE items and 17 CFE items.

b. Urine hose needs to be lengthened so that it will reach under the cabin pressure relief valve.

c. An alinement mark is needed on the television camera for cable attachment.

d. A sextant adapter must be provided for the 16-millimeter camera to satisfy the requirement to photograph the LM on the lunar surface.

e. Tape recorder and spotmeter are too loose in the stowage cushions.

2. LM-5 ascent stage:

a. Crew equipment shortages included 15 GFE items and 6 CFE items.

b. The lunar overshoes were improperly marked.

c. The COAS lens needs cleaning.

d. The PLSS hose fittings were improperly color coded.

e. The stowage location of the PLSS remote control unit connector dust cap needs to be defined.

3. LM-5 descent stage:

a. Crew equipment shortages included 10 GFE items and 4 CFE items.

b. Standard alinement markings for installation of the television camera lenses need to be incorporated.

c. The compatibility between the extravehicular gloves and the knurled handles of the television camera and of the lunar surface hammer needs to be examined.

March 3 to 13, 1969.- The third manned Apollo flight was conducted. Apollo 9, the first manned flight of the LM, qualified the LM for lunar operations. The mission consisted of an Earth orbit rendezvous and the first Apollo EVA. It was concluded that the concepts and operational functioning of the spacecraft/crew interfaces (including

procedures, provisioning, restraints, and displays and controls) were satisfactory for manned LM functions. The mission also verified the interfaces between the CM and the LM, both while docked and undocked.

The Apollo 9 mission experienced seven crew station anomalies within each vehicle. The CM problems consisted of four display and control component anomalies, a temporarily inoperative docking spotlight, interior floodlight anomalies, and mechanical difficulties in an ECS control valve. The LM problems included a tracking light failure, loss of the push-to-talk (PTT) communications mode, unexplained C&W light activations, mechanical difficulties with the forward hatch, and excessive cabin noise.

March 7 to 10, 1969.- The Apollo 11 prime and backup crews participated in LM-5 simulated altitude chamber tests and CCFF exercises at KSC. Deficiencies/discrepancies that were noted included the following.

1. Crew equipment shortages included seven GFE items.

2. The secondary and descent detents of the water tank select valve would not engage.

3. The CDR's ACA controller box had approximately 5° of mechanical "play" in the pitch axis.

4. The DSKY table was difficult to stow and unstow.

5. Velcro on the kickplate for attaching the left-hand-side stowage container was missing.

6. The LMP's engine-stop pushbutton was hard to operate because of the mechanical slop in the switch's external positive-actuation device.

March 7, 11, and 12, 1969.- The Apollo 11 prime and backup crews participated in CSM-107 simulated altitude chamber tests and CCFF exercises at KSC. Deficiencies/discrepancies that were noted included the following.

1. Crew equipment shortages included eight GFE items and six CFE items.

2. The mirror was not mounted on the LMP's couch head strut.

3. The locking mechanism on the CDR's COAS mount was sticking in the unlock position.

4. Crewmen could not hear the master alarm audio tone.

5. The scanning telescope eyepiece was loose when attached to the G&N panel.

6. One of the lower equipment bay stowage volumes was not firmly attached in the spacecraft.

March 18, 24, and 27, 1969.- The Apollo 11 prime and backup crews participated in the CSM-107 altitude chamber tests at KSC. Deficiencies/discrepancies that were noted during the tests included the following.

1. Crew equipment shortages included seven GFE items and two CFE items.

2. The CMP's oxygen umbilical would not route properly.

3. Crewmen could not hear the C&W audio tone.

4. The spacecraft lanyard for the docking target connector's dust cap was too short.

5. The hatch dump valve was binding and was improperly indexed.

6. All hand controller mounts were loose.

April 3 and 4, 1969.- The Apollo 11 prime and backup crews participated in the LM-5 descent stage CCFF test at KSC. Directions to correct the deficiencies/ discrepancies that were noted included the following.

1. Provide the flightcrew with closeout photographs of the early Apollo scientific experiments package (EASEP), the modular equipment stowage assembly (MESA), and the S-band antenna as soon as possible after closeout.

2. Schedule a later flightcrew evaluation of flight-configured items not available for review.

3. Provide markings at the end of the S-band antenna cable to denote full extension.

April 17, 1969.- The MSC spacecraft/crew integration plan for manned Block II Apollo CSM and LM missions was revised. Major changes to the plan included the following.

1. A flightcrew equipment liaison group replaced the crew equipment engineer and was established to support the FCST in the integration of flightcrew equipment with the spacecraft to support ASPO program schedules.

2. Spacecraft crew station reviews, previously designated as spacecraft crew compartment stowage reviews, would be conducted as required on an individually negotiated basis instead of being conducted for each specific spacecraft.

3. The listing of detailed checkout specifications, operational checkout procedures, and test and checkout procedures requiring flightcrew participation was redefined. The checkout exercises that were added are given in table II.

May 18 to 26, 1969.- The fourth manned Apollo flight was conducted. The Apollo 10 mission, the first lunar flight of the complete Apollo spacecraft, included a low pass over the lunar surface and the first lunar orbit rendezvous. It was concluded that the

TABLE II. - ADDITIONAL CHECKOUT EXERCISES FOR BLOCK II APOLLO CSM AND LM MISSIONS

Checkout exercise	Test location
CSM-107	
Crew equipment stowage Integration test Bench check	CSM contractor's facility
Combined systems test High-gain antenna checkout and PLSS communications test Integrated systems test Electrical mate and interface test	KSC
LM-5	
Combined subsystems test before full engineering and analysis test (FEAT) LM combined FEAT Descent-stage equipment fit and function test	LM contractor's facility
CM-LM mechanical docking EASEP/Apollo lunar surface experiments package/MESA fit and function tests Combined subsystems test Fluids testing	KSC

systems in both the LM and the CSM were operational for manned lunar landings and that the crew tasks associated with LM checkout, initial descent, and rendezvous were both feasible and practical without imposing an unreasonable crew workload.

The Apollo 10 mission experienced 12 crew anomalies, 7 in the CM and 5 in the LM. The CM problems included three display and control anomalies, intermittent annunciator warnings, couch strut discrepancies, and flaking of the CM hatch thermal coating. The LM problems included several unexplained C&W alarms, AOT contamination, and excessive cabin noise.

June 5 and 10, 1969.- The Apollo 11 prime crew participated in an LM-5 descent-stage and ascent-stage delta CCFF test at KSC. Deficiencies/discrepancies noted during the review included the following.

1. Descent stage:

   a. Crew equipment shortages included three GFE items.

   b. The manufacturer's part number label should be removed from the television cable to eliminate a possible stowage interference problem within the MESA.

2. Ascent stage:

   a. Crew equipment shortages included four GFE items and one CFE item.

   b. Several Velcro patches were missing from the spacecraft.

   c. The docking hatch would not latch to the ascent engine cover.

   d. Oxygen umbilicals were very difficult to stow and unstow.

3. Considerable rotation existed between the 70-millimeter camera and the handle.

June 10, 1969.- The Apollo 11 prime crew participated in a CSM-107 delta CCFF exercise at KSC. Deficiencies/ discrepancies noted during the review included the following.

1. The center crewman's fecal containment subsystem should be deleted.

2. Rotational controller 2 would not ratchet at the controller/mount interface.

3. The left-hand-side window shade does not fit properly.

4. The sextant 16-millimeter magazine should be identified by film type and camera speed and for use with sextant.

June 18, 1969.- The Apollo 11 prime crew participated in an LM-5 descent-stage bench check of MESA stowage items. The closeup stereocamera was modified at the review by removal of one of two Teflon mounting clips and rework of

the tabs on the two deployment lanyards to make them stand out better. Following this modification, the flightcrew stated that all equipment was acceptable for flight.

July 1, 1969.- The stowage locations for the Apollo 11 flight data file subassemblies were defined by the FCST. Components of the CSM-107 flight data file were stowed in four separate stowage locations (R1, R12, R3, and the PGA pockets). All the components in the LM were stowed in the LM flight data file compartment. The flight data files were composed of the following documents.

1. CSM-107 flight data file assembly:

Entry Operation Checklist
CMP Solo Book
CSM Lunar Landmark Maps
Alternate Flight Plan
CSM Malfunction Procedures
Flight Plan
CSM Updates
CSM Systems Data
Operation Checklist
Alternate and Contingency Checklist
CSM Data Card Kit
LM Transfer Data Card Kit
Earth Orbital Map
Target of Opportunity Chart
Launch Operation Checklist

2. LM-5 Flight Data File assembly:

LM Lunar Surface Checklist
LM Postdocking and Contingency Checklist
LM G&N Dictionary
LM Malfunction Procedures
LM Systems Data
LM Data Card Book
LM Rendezvous Checklist

July 16, 1969.- By launch, the Apollo 11 prime crew had participated in approximately 40 spacecraft and flightcrew equipment reviews at KSC. These reviews were as follows:

Bench check (CM and LM)
MESA bench check
Cabin familiarization (CM and LM)
Egress training for the altitude chambers
Simulated altitude chamber tests
"Mini" CCFF (CM and LM)
Altitude chamber tests
Descent stage CCFF
PTT switch location selection (LM)
EASEP compartment fit and function
EASEP bay closeout
Decal selection
Erectable S-band antenna handle inspection
Delta CCFF LM (ascent stage and descent stage) and CM (at pad)
EMU CCFF, delta EMU CCFF, and flight EMU CCFF
Closeup stereocamera fit check
MESA preflight bench check
Safety walkdown of pad 39A
MESA closeout
Flight readiness test (CM and LM)
Countdown demonstration test
Preflight bench check (CM and LM)

July 16 to 24, 1969.- The fifth manned Apollo flight and the first manned lunar landing was accomplished. The Apollo 11 mission accomplished the basic objective of the Apollo Program – men were landed on the lunar surface and returned safely to

Earth. The Apollo 11 mission experienced three CM and five LM crew station anomalies. The CM anomalies included the failure of an EL segment in the EMS alphanumeric readout, an unexplained master alarm activation, and an intermittent ECS control valve. The LM anomalies included the failure of an EL segment in the abort guidance system (AGS) data entry and display assembly (DEDA) data register, computer alarms during landing, the failure of the mission timer, circuit breaker impact problems, and transient indications from the RCS jet failure detection logic.

MISSION EXPERIENCE

Apollo 7 Mission

The Apollo 7 mission was the first manned flight of the Apollo Program. In the Apollo 7 mission report, it was concluded that all objectives were effectively accomplished and that the mission was successful in every respect. Specific conclusions drawn relative to CM crew station design and operations included the following.

1. The CM was qualified for operation in the Earth-orbital environment and was ready for flight tests in the cislunar and lunar-orbital environments.

2. The concepts and operational functioning of the spacecraft/crew interfaces, including procedures, provisioning, accommodations, and displays and controls, were acceptable.

3. The capability of performing a CM-active rendezvous, with only optical and onboard data, was demonstrated.

4. Navigation techniques, in general, were demonstrated to be adequate for lunar missions.

The Apollo 7 flightcrew found that the CM crew station was adequately configured for the mission and caused no compromise of crew performance of required duties. All areas of the cabin proved to be readily accessible, and most work could be performed without the use of restraints. Donning and doffing pressure suits was much easier in a weightless state than in a one-g environment and created no problem for the crew. Stowage techniques and procedures were considered to be good. The displays and controls and the lighting proved satisfactory except for a periodic problem with sunglare on the instrument panel. Visibility through the spacecraft window ranged from good to poor because of a contamination problem caused by window sealant compound outgassing.

Six crew station anomalies occurred on the Apollo 7 mission: four relative to displays and controls, one relative to lighting, and the visibility problem previously mentioned. Display and control anomalies included (1) a sudden 160° shift in the pitch axis of the attitude indicator when the attitude source was switched from G&N to the SCS, (2) the temporary failure of a rotational hand controller (RHC) to generate minimum impulse commands, (3) the failure of the delta-V and range-counter circuits of the EMS, and (4) the cracking of the window glass of both mission timers. The secondary

lamps of the floodlights in the LEB failed during the mission, and window visibility was reduced because of a buildup of film on the glass surface.

Anomalies that occurred on the Apollo missions were generally resolved by using one (and sometimes a combination) of the following four methods: (1) no change because of randomness and low criticality of failure, (2) additional hardware testing or screening, (3) hardware modification, or (4) procedural change (in onboard and/or ground operations).

For the Apollo 7 mission, the attitude indicator and RHC anomalies were resolved by method 1, the EMS anomaly by method 2, the mission timer problem by method 3 (transparent tape was placed over glass windows of subsequent indicators), the floodlight problem by methods 2 and 4 (in subsequent vehicles, only the secondary lamp would be used on "full bright" during ground tests), and the window visibility problem by method 4 (room-temperature-vulcanized (RTV) material used in window areas on the Apollo 9 and subsequent spacecraft would be precured in a vacuum at elevated temperatures instead of being room cured).

Apollo 8 Mission

The Apollo 8 mission was the second manned flight of the Apollo Program and the first manned lunar-orbital mission. The success of the Apollo 8 mission contributed significantly to the development of a lunar-landing capability. Specific conclusions drawn relative to CM crew station design and operations included the following.

1. The CSM systems were operational for manned lunar flight.

2. The navigation techniques developed for translunar and lunar-orbital flight were more than adequate.

3. Nonsimultaneous sleep periods adversely affected the normal circadian cycle of each crewmember and provided a poor environment for undisturbed rest.

Relatively few problems were encountered in regard to crew station design and operations. Equipment stowage, displays and controls, and lighting were found to be adequate. A modified kitchen timer, carried at the suggestion of the Apollo 7 crew, proved very useful for timing routine crew station operations, such as fuel cell purges. Glare shields that had been placed over certain displays to eliminate the Sun-shaft problem encountered during the Apollo 7 mission proved ineffective. Supplemental-information decals installed on the instrument panels before the flight proved very helpful to the crew. The CM windows became contaminated early in the flight, as was expected, because the design fix for this problem (earlier encountered on the Apollo 7 mission) could not be made effective until the Apollo 9 mission because of schedule constraints.

Three crew station anomalies were experienced during the Apollo 8 mission. One anomaly concerned abnormal indications from the delta-V and scroll (g/velocity trace) of the EMS at different times during the mission. A second anomaly concerned disconcerting noise from the cabin fans. The third crew station anomaly was the window problem previously mentioned. The EMS anomaly was resolved by method 1

(previously defined in the Apollo 7 mission discussion) and the cabin fan anomaly by method 4. (Cabin fans would be deenergized during general crew station operations on subsequent missions.) The disposition of the window anomaly was discussed in the previous section.

Apollo 9 Mission

The Apollo 9 mission was the first manned flight of the LM and was performed to qualify this portion of the Apollo spacecraft for lunar operations. Specific conclusions relative to CM and LM crew station design and operations included the following.

1. The onboard rendezvous equipment and techniques of both spacecraft provided the precision required for the lunar-landing missions.

2. The functional operation of the docking process was demonstrated as was the criticality of proper lighting conditions for docking.

3. The practicality of extravehicular crew transfer in the event of a contingency was demonstrated.

4. The concepts and operational functioning of the spacecraft/crew interfaces (including procedures, provisioning, restraints, and displays and controls) were satisfactory for manned LM functions. The interfaces between the two spacecraft, both while docked and undocked, were also verified as being satisfactory.

Seven CM crew station anomalies occurred during the Apollo 9 mission. The increase over the number involved in previous missions was caused by additional mission complexities and the interfaces associated with two-vehicle operation. The anomalies consisted of (1) erroneous indications of the docking status indicator during separation and docking; (2) EMS failure to scribe during entry; (3) unexplainable alarms from the propellant utilization and gaging system (PUGS), which indicated an excessive propellant imbalance; (4) unexplainable activation of the master alarm, without C&W activation, coincident with docking; (5) inoperativeness of the docking spotlight (mounted on the SM) before rendezvous; (6) floodlight failures and odors; and (7) difficulties in operating the CM surge tank shutoff valve.

The docking indication anomaly was resolved by method 4 (as defined in the discussion of the Apollo 7 mission). Docking procedures were changed to specify holding of the extend/release position until physical separation. The EMS anomaly was resolved by methods 2 and 3; the PUGS alarm anomaly by methods 3 and 4 (the C&W input to the master alarm was disconnected, and a new ground procedure was established for adjustment of PUGS instrumentation sensors); the master alarm anomaly by method 1; the docking light anomaly by method 4 (the light was inoperative because of a failure to include in the checklist the activation of the docking-light circuit breaker before spotlight deployment); the floodlight anomalies by methods 1 and 4 (the floodlights would be operated in the full-bright configuration to reduce cathode erosion and in a single-lamp mode to eliminate any burn threat to the crew); and the surge tank valve anomaly by method 4 (the problem, caused by misalinement of the valve detent position markings, was resolved by closer inspection of subsequent vehicles).

Seven crew station anomalies were also experienced with the LM flown on the Apollo 9 mission. These anomalies consisted of (1) a tracking light failure shortly after LM staging, (2) failure of the LMP's PTT communications mode toward the end of the mission, (3) a C&W alarm during AGS activation, (4) binding of the forward hatch when opened for EVA, (5) failure of the forward hatch to remain open for EVA, (6) excessive noise in the LM, and (7) unexplainable illumination of the "operator error" light upon actuation of the DEDA "clear" pushbutton.

The tracking light anomaly was resolved by methods 2 and 3; the PTT communication problem by methods 1 and 4 (additional troubleshooting procedures were developed); the AGS C&W anomaly by method 1; the hatch anomalies by method 3 (dimensions and clearances were modified, and a door snubber was added); the noise problem by methods 2, 3, and 4 (subsequent noise measurements in another LM vehicle illustrated the need to reduce the overall noise level in the cabin; this reduction was enabled by operating only one cabin fan when cooling was required and by providing earplugs for the crewmen); and the DEDA light anomaly by method 3. On the Apollo 11 spacecraft (and all subsequent Apollo spacecraft), all DEDA mode pushbuttons were modified by connecting the output of redundant switches within the pushbuttons so that closure of either switch could initiate a necessary function.

Apollo 10 Mission

The Apollo 10 mission was the first lunar flight of the complete Apollo spacecraft. The purpose of the mission was to confirm all aspects of the lunar-landing mission, exactly as it would be performed, except for the actual descent, landing, lunar stay, and ascent from the lunar surface. Specific conclusions drawn relative to CM and LM crew station design and operations included the following.

1. The systems in both the LM and the CSM were operational for a manned lunar landing.

2. Crew tasks associated with LM checkout, initial descent, and rendezvous were both feasible and practical and did not constitute an unreasonable crew workload.

During the Apollo 10 mission, fewer crew station anomalies occurred (seven for the CM and five for the LM) than during the Apollo 9 mission. Except for a problem with cabin noise, none of the anomalies were repeats of the Apollo 9 experiences; in fact, all were associated with different equipment or circuits.

The CM anomalies were (1) minor oscillations of the crewman's couch occurred during launch because of the improper configurations of the couch stabilizer, (2) the GDC exhibited excessive drift in the roll and yaw axes, (3) the EMS scribe function (acceleration/velocity) was intermittent before entry, (4) flaking of the CM hatch thermal coating occurred when the LM was first pressurized, (5) redundant lamps in the launch vehicle engine warning annunciators were intermittent during prelaunch lamp tests, (6) the digital event timer gained and lost time during certain mission phases, and (7) the left-hand head-strut lockout handle was found to be in the locked position during postflight inspection.

The CM couch stabilizer anomaly was resolved by method 4 (mandatory inspection of the stabilizer configuration would be required as part of the preingress inspection on subsequent missions), the GDC anomaly by method 2, the EMS scribe anomaly by method 3 (a new type of scroll emulsion was used on later missions), the hatch coating anomaly by method 3 (hatch insulation was replaced with a single layer of H-film tape), and the launch vehicle annunciator and event timer anomalies by method 2. The head-strut discrepancy found during the postflight inspection was resolved by method 4 (the lever spring of the strut's lockout handle was found to have insufficient force to prevent the hood from returning to the locked position; a mandatory inspection point was subsequently added to the manufacturing process to ensure proper assembly and operation).

The LM anomalies included (1) a gimbal drive actuator (GDA) failure indication during the CM-LM phasing maneuver, (2) the occurrence of three master alarms during the same maneuver, (3) AOT problems (hairlike objects on the reticle and loss of the peripheral portion of the AOT field of view), (4) excessive noise in the cabin, and (5) ascent propulsion warning light illumination with first ascent engine firing.

The LM GDA failure indication was resolved by method 3 (the brake mechanism and instrumentation logic were redesigned on later vehicles to prevent false failure indications caused by transient gimbal movements), the master alarm anomalies by method 3 (the descent propellant low-quantity signal to the C&W system was disabled to prevent nuisance triggering), the AOT anomalies by methods 1 and 4 (the prism and reticle of later AOT's received additional cleaning and inspection to prevent contamination), and the noise problem by method 4 (earplugs would be available for optional crew use during sleep periods on future missions). The ascent propulsion warning light anomaly was resolved by methods 1 and 4. The probable cause of the indication was considered to be the uncovering of a low-level propellant sensor by a gas bubble formed as a result of the low (50 percent) propellant load and ullage required for the particular mission. Larger fuel loads, longer ullages, and the existence of a 1/6-g lunar environment prevented a repeat of this anomaly on later flights.

Apollo 11 Mission

The Apollo 11 mission resulted in the accomplishment of the basic objective of the Apollo Program: men were landed on the lunar surface and returned safely to Earth. Specific conclusions drawn about CM and LM crew station design and operations included the following.

1. Manual control in maneuvering the LM to the desired landing point was satisfactorily exercised.

2. Lunar surface prelaunch operations were well planned and executed.

3. The time-line activities for all phases of the lunar-landing mission were well within the crew's capability to perform the required tasks.

4. The hardware problems experienced on the mission, as on previous manned missions, did not unduly hamper the crew or result in the compromise of safety or mission objectives.

During the Apollo 11 mission, three CM crew station anomalies and five LM crew station anomalies were experienced. Except for a problem with the LM mission timer, none of the anomalies had been experienced on earlier Apollo flights.

The CM anomalies included (1) a one-digit loss in the EL segment of the EMS velocity indicator, (2) the occurrence of master alarm activation during LM pressurization, and (3) intermittent glycol temperature control valve authority. The EMS and master alarm anomalies were resolved by method 1 (a generic problem was considered unlikely after considering the total hardware experience), and the glycol temperature control problem was resolved by method 2 (a detailed inspection was made of valves installed on subsequent vehicles).

The LM anomalies included (1) an inoperative mission timer shortly after lunar landing, (2) the occurrence of several guidance computer program alarms during lunar landing, (3) a one-digit loss in the EL segment of the data register for the AGS DEDA, (4) the breaking of a circuit breaker knob and the inadvertent closing of two other circuit breakers during lunar stay, and (5) RCS thrust chamber assembly flags indicating sporadic malfunctions of the jet firing logic.

The LM mission timer anomaly was resolved by method 3 (new timers, of a different source and design, were procured). The computer program alarm anomaly was due to noncritical interrupts of the computer's executive program caused by peakload processing of rendezvous radar (RR) data; this anomaly was handled by method 3. (The computer software of subsequent LM's was modified to ignore counterinterrupts from the RR coupling data units.) The DEDA EL anomaly was resolved by method 1, the circuit breaker problem by method 3 (additional guards were installed to prevent the oxygen purge system – the top portion of the PLSS – from impacting the circuit breakers), and the RCS flag anomaly by method 1.

In summary, 43 crew station anomalies were experienced on the first five manned Apollo missions. This number was approximately one-third of the total anomalies reported. Except for problems with the EMS, the event and mission timers, and the crew station noise, the crew station anomalies were unique and nongeneric. Fourteen of the anomalies were resolved by method 1 (no change required because of randomness and low criticality of failure), 9 by method 2 (additional hardware testing or screening), 12 by method 3 (hardware modification), and 8 by method 4 (procedural changes). Problems with the EMS occurred on each Apollo mission; the problems were nongeneric, however, and therefore received a variety of corrective actions. Problems with the Apollo mission timers and the LM event timer were eventually resolved by procuring redesigned timers. The noise problem was resolved by powering down certain equipment and by using earplugs during certain mission phases.

CONCLUSIONS AND RECOMMENDATIONS

The Apollo crew station design and development was not a radical departure from that of previous aerospace programs. However, certain state-of-the-art equipment and techniques that will be of use in future programs were developed. The task of Apollo crew station design and development was complicated by the number and complexity of physical and operational interfaces that existed.

The success of the Apollo crew station effort was attributable to four basic factors: (1) the use of knowledge gained from prior aerospace experience and practices; (2) the study, review, and simulation of new state-of-the-art designs and operations; (3) the ability to control the numerous physical and operational interfaces that existed; and (4) the effective communications and information dissemination between program organizational elements.

The tools, techniques, and requirements used for Apollo crew station design and development were state-of-the-art devices, procedures, and requisites that are generally suited for use in follow-on programs. Consequently, crew station specification documents pertaining to displays and controls; markings, labeling, and color; environmental criteria; lighting; extravehicular and intervehicular activity support equipment; location coding; and loose equipment and stowage have been generated at the NASA Lyndon B. Johnson Space Center (formerly the Manned Spacecraft Center). These specifications will serve as a medium for transferring Apollo (and earlier) crew station experience to subsequent programs.

As a result of the Apollo experience, three areas were identified that will require special attention in future crew station development efforts. Recurrent problems existed with crew station acoustics, instrument glass (breakage), and caution and warning systems. For the benefit of post-Apollo design efforts, specifications and standards have been published that are intended to circumvent problems in these areas. Recommended engineering approaches to these three potential problem areas are as follows.

1. Crew station acoustics: An integrated approach toward noise reduction is required, including the early application of MSC Design and Procedural Standard 145, "Acoustic Noise Criteria," and the criteria contained in other Lyndon B. Johnson Space Center and military standards.

2. Instrument glass: Application of MSC Design and Procedural Standards 41 and 144, "Shatterable Material – Exclusion from Crew Compartment" and "Windows and Glass Structure," should ensure the proper selection and testing of all crew station glass and thus circumvent the type of instrument glass failures experienced on Apollo missions.

3. Caution and warning systems: Designs that conform to the functional requirements contained in MSC Specification SC-D-0007, "Displays, Manned Spacecraft and Related Flightcrew Equipment, Functional Design Requirements for," should negate many of the problems experienced with the Apollo caution and warning systems. Design features that would help reduce nuisance triggering include (1) conversion to an "all digital" system, (2) ease of access for recalibration of caution and warning signal levels and modification of transient control circuitry, and (3) provision of crew inhibits for each caution and warning channel.

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